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**Evaluation of Available
Cleanup Technologies for
Uncontrolled Waste Sites**

Office of Technology Assessment, Washington, DC

Prepared for

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FINAL REPORT

**EVALUATION OF AVAILABLE CLEANUP
TECHNOLOGIES FOR UNCONTROLLED WASTE SITES**

FOR

THE OFFICE OF TECHNOLOGY ASSESSMENT

U.S. CONGRESS

by

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EXECUTIVE SUMMARY

This report presents an evaluation of cleanup technologies for remedial action at uncontrolled waste sites. For presentation purposes cleanup technologies are divided into two classes: containment and treatment. Containment technologies function primarily to isolate contaminants already in place in order to prevent harmful exposure to the environment and human populations. Treatment techniques function by destroying the inherent hazardous properties of the contaminants, or by separating them from environmental media that are the present or potential sources of human and environmental exposure. For the latter function, separations additional treatment or disposal may be required for the hazardous residues that are removed. Cleanup activities are presently taking place at many sites. Most of the efforts to date have been directed toward initial responses such as removal or remedial investigations and feasibility studies to determine the most appropriate response. Remedial programs implementing containment and treatment technologies are in place at a limited number of sites.

There is a wide variety of individual containment and treatment cleanup technologies presently available. See Exhibits 1 and 2 for a summary of their principal technical features that influence the selection process.

These individual techniques can and are being used in combinations ranging from systems based primarily on containment to systems using treatment primarily. Treatment processes are often used in combinations to handle the complex and mixed wastes found at most cleanup sites. Successive treatment by several techniques may be required to comply with criteria and standards set to protect human health and the environment.

Most of the techniques are relatively untested in cleanup situations. Little or no long-term performance data are available for containment systems. As a consequence, careful long-term post installation monitoring should be carried out.

An examination of remedial installations in place indicates that containment has been the primary technology selected at many sites. The reasons appear to be as much institutional as technical. Institutional considerations are important in the selection process and may be the primary determinant in some cases. The definitions and practical interpretations of cost and effectiveness will influence the general nature of the selection process. Application of the cost-effectiveness criterion, used in the early Superfund analytic process, focussed on short-term characteristics, particularly for containment options.

In essence, the cost computations ignored or downplayed long-term costs of repair, replacement, monitoring, and possibly upgrading. Similarly, the effectiveness to protect public health and the environment has been assumed to last indefinitely. For treatment

strategies, these issues do not arise since, in a successful project, the contamination is reduced permanently to a level consistent with adequate protection.

Another institutional factor is the cost shearing rules used to allocate costs between the states and the Federal government. For private sites, the present formula allocates 90% of the initial costs to the Federal government and 10% to the states. But the states must pay 100% of the continuing costs. The states who are taking more of the total responsibility for managing cleanup would prefer technologies with low continuing costs. With the short-term view, as expressed in the paragraph above, containment systems tend to display high capital and low operating and maintenance (O&M) costs relative to treatment systems. Cost comparisons are very sensitive to site-specific characteristics and this tendency may not be exhibited at particular sites. The selection process involves both sets of the above players, as well as the interested parties, and is designed to reach a mutually agreeable decision, but it may not work as planned in all instances.

Containment processes can be put in place without the need for permits. Some states are, on the other hand, considering imposing RCRA or similar requirements on some on-site treatment processes, particularly incineration. The time that would be required to obtain such permits and the difficult political process involved appears to disfavor treatment from a decision-maker's viewpoint.

The institutional context is changing. Cost considerations look out farther in time and involve more extensive applications of present value (discounting) techniques. But they still do not include potential long-term costs as replacement nor monitoring beyond a few decades. The effectiveness side of the decision equations is also changing. More emphasis is being placed on risk assessment, including probabilistic considerations of future events. The latest draft of the National Contingency Plan (NCP) includes a number of fixed criteria which could be applied to establish a level to which the contamination must be reduced.

With this background, the outlook for the application of the various technologies is summarized in Exhibits 3 and 5 for containment and treatment technologies, respectively. Exhibits 4 and 6 contain keys to the codes in the other two exhibits. The treatment technologies, based on a variety of chemical, physical, or biological principles, include a number of approaches capable of high cleanup efficiencies for soils and groundwater contaminated with both organic and inorganic pollutants.

As a last note, current Federal policies strongly favor the application of established technologies. Given the potential health risk and costs involved, this approach is appropriately prudent. But it, in essence, precludes the selections of emerging techniques with

technical and economic promise and may inhibit the overall innovative process. This situation could be offset and perhaps reduced through a Federally-supported demonstration program in which new technologies were evaluated in the field.

EXHIBIT 1

CONTAINMENT TECHNOLOGIES - SUMMARY

Technology	Advantages	Disadvantages	Limitations
<u>Groundwater Barriers</u>			
- Slurry Wall	Most versatile, best understood barrier technology. Can be inexpensive compared to other barrier techniques Low O&M	Requires excavation Requires site area to mix backfill. Difficult to verify continuity of slurry or backfill. Difficult to key to bedrock.	Must tie to impervious zone Not 100% impermeable Long-term effects of some chemicals on permeability uncertain.
- GROUT CURTAIN	Minimal site disturbance. No excavation required. Low O&M	Chemicals in the grout may cause site safety or environmental problems. Difficult to verify continuity of wall. Limited applicability. Expensive compared to other barriers. Difficult to key to bedrock.	Less than 20% soil can pass No. 200 sieve. Must tie to impervious zone. Not 100% impermeable. Long-term effects of some chemicals on permeability uncertain.
- Vibrated Beam	Special slurries improve chemical compatibility. No excavation required. Low O&M	Very sensitive to construction quality. Difficult to verify continuity of wall. Difficult to key to bedrock. Relatively new technology.	No obstructions in soil. Must tie to impervious zone. Access for large crane needed. Not 100% impermeable. Long-term effects of chemicals on permeability uncertain.

EXHIBIT 1

CONTAINMENT TECHNOLOGIES - SUMMARY (continued)

Technology	Advantages	Disadvantages	Limitations
- Sheet Pile	No excavation required. Low O&M	Expensive Difficult to key to bedrock. Continuity of wall at joints difficult to verify.	Soils must be loosely packed. Limited to about 50 ft. Must tie to impervious zone. Not 100% impermeable. Some chemicals may attack piling material.
- Block Displacement	No underlying impervious zone needed.	Technology under development. Continuity is difficult to verify.	Site conditions must conform to complex design requirements.
<u>Groundwater Pumping</u>			
- Wall Points	Proven and well understood. Can function for very long periods. High design flexibility. High reliability. Useful in many situations. Effectiveness can be verified.	Design may require expensive modeling. Long-term O&M required. Performance sensitive to design. Collected liquid must be treated or disposed of.	Useful up to 10 meters. Will not affect contaminants in unsaturated zone or which do not flow.
- Deep Well Systems	Same as wall points.	Same as wall points.	Same as wall points; except useful to any depth.

EXHIBIT 1

CONTAINMENT TECHNOLOGIES - SUMMARY (continued)

<u>Technology</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Limitations</u>
<u>Subsurface Drains</u>	Proven and well understood. Low O&M Superior to wells under certain conditions. Less sensitive to design than wells. Conceptually simple.	Less flexibility than wells. Susceptible to clogging. Excavation required. Collected liquid must be treated or disposed of.	Difficult to install beneath waste site. More cost-effective in shallow applications.
<u>Runon/Runoff Controls</u>	Proven and well understood. Inexpensive. Effectiveness desirable. Only conceptual design required.	Periodic inspection and maintenance required.	May not be able to handle abnormal storm.
<u>Surface Seal/Caps</u>	Inexpensive compared to excavation and removal. May be used as an interim measure where surface infiltration is a problem.	Periodic inspection and maintenance required.	Difficult for very large sites, or if obstructions are present. Subject to potential failure, without proper design, installation and maintenance.

EXHIBIT 1

CONTAINMENT TECHNOLOGIES - SUMMARY (continued)

<u>Technology</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Limitations</u>
<u>Solidification and Stabilization</u>	Improves containment performance. High short-term effectiveness possible. Waste material (e.g. fly ash, kiln dust) can be used as pozzolan.	Extensive testing may be required. Many processes developmental.	Long-term integrity uncertain. Not useful for many organics.
<u>Encapsulation</u>	Improves effectiveness of land disposal.	Developmental	Long-term integrity uncertain. Requires solidification of bulk wastes.
<u>Vitrification</u>	No excavation required.	Technology under development.	Site conditions must conform to narrow range of site and waste characteristics.

EXHIBIT 2

TREATMENT TECHNOLOGIES - SUMMARY

Technology	Advantages	Disadvantages	Limitations
<u>Restoration/Rehabilitation Processes</u>			
<u>Biological Treatment</u>			
- Conventional	Applicable to many organic waste streams. High total organic removal. Inexpensive. Well understood and widely used in other applications.	May produce a hazardous sludge which must be managed. May require pre-treatment prior to discharge.	Micro-organisms sensitive to oxygen levels, temperature, toxic loading, inlet flow. Some organic contaminants are difficult to treat. Flow and composition variations can reduce efficiency.
- In-Situ Biodegradation	Destroys waste in place.	Limited experience. Extensive testing may be required. Containment also required.	Aeration difficult to depths greater than two feet. Many common organic species not easily degraded. Needs proper combination of wastes and hydrogeological characteristics. Obtaining proper mix of contaminants, organisms, and nutrients. Organisms may plug pores.

EXHIBIT 2

TREATMENT TECHNOLOGIES - SUMMARY (continued)

<u>Technology</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Limitations</u>
<u>Chemical Treatment</u>			
- Hot Air Oxidation	Good for wastes too dilute for incineration or too concentrated or toxic for biological treatment.	Oxidation not as complete as thermal oxidation or incineration. May produce new hazardous species. Extensive testing is required. High capital investment.	Poor destruction of chlorinated organics. Moderate efficiencies of destruction (40-90%).
- Chlorination for CH	Essentially complete destruction. Well understood and widely used in other applications.	High level of operator skills required. May require post-treatment.	Interfering waste constituents may limit applicability or effectiveness.
- Ozonation	Can destroy refractory organics. Liquids, solids, mixes can be treated.	Oxidation not as complete as thermal oxidation or incineration. May produce new hazardous species. Extensive testing is required. High capital investment; high O&M.	Not well understood.

EXHIBIT 2

TREATMENT TECHNOLOGIES - SUMMARY (continued)

<u>Technology</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Limitations</u>
- Radiation for Chromium	High destruction. Well understood and widely used in other applications.	Specialized for Cr.	Interfering waste constituents may limit applicability or effectiveness.
- Permeable Treatment Beds	Limited excavation required. Inexpensive.	Developmental. Periodic replacement of treatment media required. Spent treatment medium must be disposed of.	Best for shallow plumes. Many reactants treat a limited family of wastes. Effectiveness influenced by groundwater flow variations.
- Chemical Injection	Excavation not required. No pumping required.	Developmental. Extensive testing required.	Best for shallow plumes. Need fairly homogeneous waste composition.
<u>Incineration</u>			
- Conventional Incineration	Destroys organic wastes (99.99%).	Disposal of residue required. Test burn may be required. Skilled operators required. Expensive.	

ANNEX 2

TREATMENT TECHNOLOGIES - SUMMARY (continued)

Technology	Advantages	Disadvantages	Limitations
- Co-flo	Destroys organic wastes (99.99%). Transportation of wastes not required.	Disposal of residue required. On-site feedstock preparation required. Feed burn may be required. Skilled operators required. Expensive.	Mobile units have low feed rate.
- Thermal Oxidation for Gaseous	Proven technology. High destruction efficiencies. Applicable to most organic streams.	May require auxiliary fuel. O&M cost can be high.	
- Incineration/Transfer Processes			
Chemical			
- Neutralization/Precipitation	Wide range of applications. Well understood and widely used in other applications. Inexpensive.	Residue sludge produced.	Complexing agents reduce effectiveness.
- Ion Exchange	Can recover metals at high efficiency.	Generates sludge for disposal. Pre-treatment to remove suspended solids may be required. Expensive.	Resin fouling. Removes some constituents but not others.

EXHIBIT 2

TREATMENT TECHNOLOGIES - SUMMARY (continued)

<u>Technology</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Limitations</u>
<u>Physical Treatment</u>			
- Carbon Adsorption for Aqueous Streams	Well understood & demonstrated. Applicable to many organics that do not respond to biological treatment. High degree of flexibility in operation and design. High degree of effectiveness.	Regeneration or disposal of spent carbon required. Pretreatment may be required for suspended solids, oil, grease. High unit cost.	Many inorganics, some organics are poorly adsorbed.
- Carbon Adsorption for Gases	Widely used, well understood. High removal efficiencies.	High capital and O&M costs.	More effective for low molecular weight, polar species. Despense: or regeneration of spent carbon required.
- Flocculation, Sedimentation and Filtration	Low cost. Well understood.	Consentee always for disposal.	
- Stripping	Well understood and demonstrated.	Air controls may be required.	Applicable only to relatively volatile organic contaminants.

TREATMENT TECHNOLOGIES - SUMMARY
(continued)

<u>Technology</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Limitations</u>
- Flotation	Well understood and demonstrated. Inexpensive.	Generates sludge for disposal.	
- Reverse Osmosis	High removal potential.	Generates sludge for disposal. Pretreatment to remove suspended solids or adjust pH may be required. Expensive.	Variability in waste flow and composition affects performance.
- Extraction	Greater control possible than with solution mining. Avoids disposal of contaminated soil.	Excavation and liner construction required. Collection and treatment of elutriate required.	Treated soils may still contain unacceptable levels of contaminants.
- Solution Mining	Removes contaminants from unsaturated zone. Excavation not required.	Collection and treatment of elutriate	Treatment is non-uniform and may bypass regions of contamination.

EXHIBIT 3

FUTURE USE OF CONTAINMENT TECHNOLOGIES

(For Key to Codes See Exhibit 4)

<u>Technique</u>	<u>Applicability</u>	<u>Effectiveness</u>	<u>Confidence</u>	<u>Cost</u>	<u>Cap/Own</u>	<u>Projected Level Of Use</u>
<u>Barriers</u>						
Slurry Wall	1	1	2	2	1	Extensive
Grout Curtain	2-3	1	2	2-3	1	Limited
Vibrating Beam	2	1	2-3	2-3	1	Moderate
Sheet Pile	3	1-2	2	2-3	1	Nil-Limited
Block Displacement	3	1	4	3	1	Nil
<u>Hydraulic Controls (Walls)</u>	1	1,3	1	1	3	Extensive
<u>Subsurface Drains</u>	2	1	2	1	2	Moderate
<u>Runon/Runoff Controls</u>	1	3	1	1	2	Extensive
<u>Surface Seals and Caps</u>	1	2,3	2	1	1	Extensive
<u>Solidification, etc.</u>	2	1,3	3-4	2	1	Moderate-Limited
<u>Vitrification</u>	3	1	4	3	1	Nil

EXHIBIT 4

FACTORS USED TO RATE CONTAINMENT TECHNIQUES

APPLICABILITY

- 1 - Very broadly applicable; little or no site dependency
- 2 - Broadly applicable; some sites unfavorable
- 3 - Limited to sites of specific characteristics

EFFECTIVENESS

- 1 - Can produce "leak-tight" containment
- 2 - Can reduce migration - some leakage likely
- 3 - Used as supporting technique in conjunction with other elements

CONFIDENCE

- 1 - Well proven - long-term effectiveness - high
- 2 - Well proven - long-term effectiveness - unknown
- 3 - Limited experience; used in other applications
- 4 - Developmental; little data

COST FOR FUNCTION PROVIDED

- 1 - Low
- 2 - Normal
- 3 - High

CAPITAL TO O&M COST RATIO

- 1 - Capital higher than O&M
- 2 - Capital about same as O&M
- 3 - Capital lower than O&M

EXHIBIT 3

FUTURE USE OF TREATMENT TECHNOLOGIES

(For Key to Codes See Exhibit 6)

Techniques	Applicability Effectiveness Confidence Cost			Secondary Projected Level		
	Or, 1-2	2	1	Cap/OM	Disposal	Use of
<u>Biological Treatment</u>						
<u>Chemical</u>						
Neutralization/	In, 1	1	1	2	4	Moderate-Extensive
Precipitation						
Wet Air Oxidation	Or, 2	2	2	1-2	3	Moderate
Chlorination (CW)	In, 3	1	2	2	1	Limited
Ozonation	Or, 3	2	3	2-3	2	Nil
Reduction (Cr)	In, 3	1	2	2	3	Limited
<u>Physical</u>						
Carbon Adsorption	Or, In, 1	1	1	2-3	2-3	Moderate-Extensive
Sedimentation/Filtration	Or, In, 1	1	1	2-3	4	Moderate-Extensive
Stripping	Or, 2	1	1	2	4	Moderate
Flotation	Or, 2	2	1	1	4	Limited
Ion Exchange	In, 3	1-3	3	3	4	Nil
Reverse Osmosis	Or, In, 3	1-2	3	3	4	Nil

EXHIBIT 5

FUTURE USE OF TREATMENT TECHNOLOGIES

(continued)

<u>Techniques</u>	<u>Applicability</u>	<u>Effectiveness</u>	<u>Confidence</u>	<u>Cost Cap/OMM</u>	<u>Secondary Disposal</u>	<u>Projected Level of Use</u>
<u>Gas Stream Controls</u>						
Thermal Oxidation	Or, 1	1	1	3	3	Limited-Moderate
Carbon Adsorption	Or, 1	1	1	3	2-3	Limited-Moderate
<u>Incineration</u>						
On-Site	Or, 1	1	2	3	1	Limited
Off-Site	Or, 1	1	1	3	3 ^a	Moderate
<u>In situ Biodegradation</u>	Or, 3	2	3	2	3	Limited
<u>Extraction</u>	Or, In 3	2	4	2	3	Nil
<u>Solution Mining</u>	Or, In 3	2	4	2-3	3	Nil
<u>Permeable Treatment Beds</u>	Or, In 3	2	3	2	1-2	Limited
<u>Chemical Injection</u>	In 3	1-2	4	2	3	Nil

Notes:

a. Must dispose solid residues.

b. Depends on reactive material used.

EXHIBIT 6

FACTORS USED TO RATE TREATMENT TECHNOLOGIES

APPLICABILITY

Class

- Or - Organic compounds
- In - Inorganic compounds

Range

- 1 - Broadly applicable to compounds in indicated class
- 2 - Moderated applicable; depend on waste composition;
concentration
- 3 - Limited to special situations

EFFECTIVENESS

- 1 - Highest levels available
- 2 - Output may need further treatment; may have pockets
untreated (in-situ)

CONFIDENCE

- 1 - Well proven - easily transferable to site cleanup
- 2 - Well proven - but not in clean-up settings
- 3 - Limited experience
- 4 - Developmental; little data

COST FOR FUNCTION PROVIDED

- 1 - Low
- 2 - Normal
- 3 - High

EXHIBIT 6

FACTORS USED TO RATE TREATMENT TECHNOLOGIES **(continued)**

CAPITAL TO O&M COST BASIS

- 1 = Capital higher than O&M
- 2 = Capital about the same
- 3 = Capital lower than O&M

SECONDARY TREATMENT OR DISPOSAL

- 1 = None
- 2 = Minor
- 3 = Major, but does not require hazardous waste techniques.
- 4 = Basically a separation process; must be used with subsequent hazardous waste treatment or secure disposal step

I. INTRODUCTION

The cleanup of uncontrolled hazardous waste sites under the aegis of federal, state, or private parties is based on the application of various types of technologies. This report focuses on those technologies utilized principally in the remedial action phase (as defined in the Federal National Contingency Plan) of the overall set of clean-up activities at a site. Techniques primarily applicable to removal such as drum overpacking, excavation, etc. are not included.

Remedial action technologies may be split, at the highest level of classification, into two somewhat arbitrary and overlapping groupings, containment technologies and treatment technologies. The primary function of containment technologies is arrest the movement of contaminants from a source, to limit the extent of already contaminated groundwater plume or soil mass, or to immobilize the contaminants to prevent or reduce exposure to humans or the environment. The function of treatment technologies is to detoxify contaminants by destroying the chemical characteristic or characteristics that render them hazardous, or by separating those characteristic materials from the environmental media that could serve as routes of exposure.

In the latter case, the output or residue from the separation process retains the hazardous properties, frequently in a more concentrated stream. These residues require proper disposal (and perhaps additional treatment) to achieve the overall objectives of protecting human health, welfare, and the environment. If the subsequent treatment and disposal steps are not properly managed, the original hazards may be shifted to other environmental media or locations and to new exposed populations.

The ultimate purpose of both sets of technologies is to reduce the potential exposure of human and ecological populations to whatever level is considered acceptable by the administrative or legal process used in establishing the remedial action program at a particular site.

The choice of technology or technologies may be limited primarily to containment methods. On the other hand, treatment technologies are generally applied in combination with some form of containment. This follows from the general functional nature of these two types of technologies. Containment techniques are designed to isolate the sources of contamination or limit the movement of contaminants as soon as the containment system is installed or brought into operation. Treatment systems, on the other hand, may require long periods of time in order to detoxify or to immobilize the contaminants present at an uncontrolled waste site. In order to prevent continuing spread of contamination during the period required for treatment, some means of containment is required contemporaneously.

Containment systems generally fall into four types. The first, based on hydrologic principles, uses walls and pumping to control the outward flow from or the potential contact of groundwater with a source of contamination. Alternatively, some sort of physical barrier such as a grout curtain or slurry wall can be installed in such a way to prevent groundwater from moving into or out of the contaminated mass of soil. The third group comprises conventional interception and drainage systems. The fourth set of technologies isolates the wastes in containers or highly impermeable matrices.

Treatment technologies may utilize one of many types of process principles. The toxicity of organic chemicals can be eliminated by degrading the specific chemical species through biological, chemical, or physical processes. Detoxification of inorganic species, such as arsenic or cadmium, is more difficult. Toxicity often resides in the element itself, which cannot be altered by any of these processes. Treatment technologies act on inorganic species by immobilization and separation, or in a few cases, by converting the form of the element to a nontoxic or less toxic form. In the first case, secure landfilling is the only current appropriate means of ultimate disposal. In the future, technologies to recovery and reuse the contaminant species may become available.

The selection of technological approaches, which often embody combinations of both the two general types, is generally dictated by statutory, regulatory, administrative, or legal criteria. These criteria most commonly emphasize some measure of cost effectiveness. This report examines and evaluates a wide range of containment and treatment technologies with respect to their effectiveness and a number of other evaluative criteria to be discussed further below.

In particular, the analysis looks beyond the immediate effectiveness of a technology. The questions in the context of this analysis shift from how will the technology work in the period immediately following installation and construction, to how well will the technology work with respect to preventing exposure to populations over the long run.

The rest of the report contains the following sections: Section II presents a discussion and evaluation of the individual technologies. In Section III, the technologies are evaluated comparatively with respect to criteria based on clean-up objectives and to the nature of the clean-up problem being considered. A selected sample of recent actions is used to provide background for the discussion. Section IV looks at the technologies, vis-a-vis, a set of institution issues, develops an outlook based on present trends and assumptions, and suggests means to change the outlook, if that becomes appropriate.

II. CONTAINMENT AND TREATMENT TECHNOLOGIES

A. Introduction

This section presents a description and evaluation of a number of technologies potentially applicable at cleanup sites. The technologies are presented in two classes; containment technologies and treatment technologies. Each discussion contains a description, factors that bear on the capability of the technology, resource requirements and a summary. A number of the technologies for these cleanup sites are drawn from more conventional applications in industrial waste treatment. Details on these technologies beyond that described herein can be found in the references provided.

The containment technologies are designed to immobilize or control the outward flow of hazardous substances from the presently contaminated site. The various techniques described range greatly in potential applicability and in expected effectiveness over long periods of operation. Treatment technologies are designed to detoxify the waste by destroying or separating the constituents that create the hazard. In actual applications, treatment technologies are often used in combinations, as noted in Section I. The techniques discussed, as in the case of containment methods, range widely in applicability and in potential effectiveness. Most containment technologies depend primarily on site factors. On the other hand, most treatment technologies are dependent on waste properties.

The following sections contain discussions on the individual technologies. In certain cases several similar technologies have been grouped together to avoid redundancy and repetitive discussion. Each technology discussed is divided into four sections: description, capability, resource requirements, and summary. Where available, information on actual performance at remedial action sites has been included.

The Description provides a short description of the technology, or group of technologies, as well as references where additional information on the technology may be found.

The Capability section is divided into three subsections. The first, Range of Applicability, gives waste and site factors which determine the technical applicability of the technology for site-specific conditions. Extent of current use is also discussed. The second subsection, Effectiveness, gives the theoretical or design capability of the technology including technical uncertainties, and discusses secondary effects of the technology. The final subsection, Reliability, discusses the expected short-term and long-term reliability of the technology based on historical experiences.

The Resource Requirements section is divided into three subsections. The first subsection, Costs, addresses the typical capital costs associated with the technology. Cost for design and testing and for operation and maintenance are also discussed when they are significant relative to other remedial technologies. Unit costs are given when possible, but it should be noted that costs for a technology at a specific site may differ significantly from typical unit costs due to a variety of site specific factors. Typical installation costs for subsurface drains, for example, are on the order of \$50/ft, while at one site installation costs were reported at over \$1600/ft. Anecdotal cost data, where available, are given to demonstrate the range of costs experienced with a given technology. All unit cost data is reported in 1984 dollars. Standard indices have been used to update unit cost data from the references using different years as a basis. Site specific costs are reported for the year in which the cost was incurred.

The second subsection addresses personnel requirements associated with the technology. Personnel requirements are only discussed when the resources required by a given technology are significantly greater than or less than what is typically required to design, install or operate remedial technologies in general.

B. Criteria For Evaluation

The number of treatment and containment combinations is nearly as varied as is the number of sites. The selection of the most appropriate technologies and their ultimate success depend on many factors, principally factors characteristic of the waste and of the site. In considering the adequacy of current and emerging technologies such as those illustrated here, it is important to look at each one in respect not only to its potential effectiveness, but also with regard to a number of other criteria.

The principal criteria for evaluation of cleanup technologies in this study mirror the technology selection factors delineated in the National Contingency Plan under CERCLA. The selection of technologies for remedial action is accomplished principally by examining the cost effectiveness of a technology or a set of technologies vis-a-vis alternatives. The criteria that will be used for the evaluation in this study are shown in Table 1.

The context for evaluation in this analysis is somewhat broader than it would be for selecting the most cost-effective technology under CERCLA. As a consequence, there are a number of criteria that deal with factors outside of the particulars of the provisions of the National Contingency Plan. Several other factors included in the National Contingency Plan as screening criteria (e.g., use of established technology) are not considered here.

TABLE 1

CRITERIA FOR EVALUATING CLEAN-UP TECHNOLOGIES

CAPABILITY

o RANGE OF APPLICABILITY

- Wastes
- Site Factors

o EFFECTIVENESS

- Design Range
- Technical Uncertainties
- Secondary Effects

o RELIABILITY

- Short Term/Operational
- Long Term/Functional
- Historical Experience

RESOURCE REQUIREMENTS

o COSTS

- Design/Test
- Capital
- Operating & Maintenance (O&M)

o PERSONNEL

- Design
- Construction/Installation
- Operating & Maintenance (O&M)

The evaluation criteria fall into two broad classes:

- (1) capability; and
- (2) resource requirements.

Capability includes factors related to the performance of the technology while resource requirements deal with the personnel and financial needs to design, install, and operate the technology.

Capability

The capability criteria include:

- o range of applicability;
- o effectiveness; and
- o reliability

Range of applicability delineates a set of situations for which a technology is, a priori, appropriate. The range depends on waste characteristics and on site factors. Waste characteristics pertain to the chemical and physical compatibility of the waste with the treatment or containment technology. Site factors include geologic, topographic, hydrologic, meteorologic and other characteristics of the site which affect technology performance. For most technologies the range of applicability can be divided into three parts. The first is a range in which the technology is clearly applicable. Second is the opposite, that is, a range where the technology is clearly inapplicable. The most difficult to characterize range is that in between where the technology may be applicable if it is appropriately engineered.

The next criterion is effectiveness. Effectiveness is the expected capacity of the technology to achieve certain remedial action objectives. The principal remedial objectives are to contain the contaminants in a prescribed volume, or to destroy or immobilize the contaminants by chemical or physical means by applying treatment processes. The effectiveness criterion considers the expected performance or design range of the technology; that is, the range of effectiveness that the technology is, in theory, capable of providing as reflected in the design basis. This range may be based on actual experience or theoretical analysis. The effectiveness criterion also addresses technical uncertainties and secondary effects of the technology. Technical uncertainties reflect the expected range of the variation in technology performance. For example, the expected effectiveness of an air stripping unit may be 95 percent under ideal conditions, but site factors may cause performance to decrease by up to 30 percent. Secondary effects include the transfer of contaminants from one environmental medium to another. A treatment technology, for example, which requires landfilling of residual materials generally is less effective on a broad scale than one which degrades or destroys the contaminants.

The third technical criterion is reliability, which can be considered from two points of view. The first is a short-term point of view dealing with the operational characteristics of the technology. This is generally more applicable to treatment technologies. It examines the potential for deviations from the design effectiveness under operating conditions. The second point of view is long-term or functional reliability. This is generally more relevant to the containment technologies. It relates to the long-term ability of the technology to maintain the function for which it was designed, for example, the ability of a grout curtain to contain contaminants after many decades have passed. The reliability criterion will consider the historical or demonstrated performance of the technologies, enabling comparison of expected vs. actual effectiveness and determination of technology reliability.

Resource Requirements

Resource requirements are quite straightforward. They are broken down into a number of categories as the technologies are expected to demonstrate significantly different requirements within the subfactors. Actual data reflecting experience at clean-up sites are sparse.

Cost requirements are conventionally broken down into three elements. The first is the costs involved at the front end, design and testing. Extensive and costly pilot testing or hydrologic surveys are required for some technologies. Capital costs include requirements for equipment, such as carbon adsorbers, or for construction and installation, as for a slurry wall where extensive field activities are needed. Operating and maintenance requirements include the costs incurred once the system is in place. Typically, these costs include personnel salaries, power, materials for treatment techniques such as carbon adsorption, and disposal if a residue is produced.

The personnel criterion is broken down in a similar fashion, with the construction/installation personnel item as the equivalent to capital costs. Personnel requirements may vary widely in magnitude and nature. Containment techniques typically require civil engineering (including hydrogeology) skills; many treatment technologies fit into the practice of chemical engineering. Installation of slurry walls calls for specially trained and equipped geotechnical crews, while some packaged treatment equipment may be easily and quickly installed by crews with process industry experience.

Costs are given for implementing the technology at a common example site. The example site is 200 ft by 200 ft and has three sources of contamination—a drum recycling area, a metals recovery operation, and a lagoon filled with sludge (4 ft x 20 ft x 20 ft). As a result of leakage and spills from these sources, groundwater has been contaminated with organic solvents and heavy metals. A 200 ft wide plume of contamination extends 800 ft offsite, and is only 2500 ft from a nearby well field. The water table is 5 feet below the ground

surface. Bedrock is sound and unfractured and begins 20 feet below the site. Groundwater travels at 1×10^{-2} cm/sec, and a groundwater treatment rate of 450 gpm is expected. Additional assumptions required to estimate costs are given with each technology. Estimated costs are generally calculated based on unit costs or data from an actual site. Actual costs incurred to implement the technology at an actual site similar to the example site may be significantly higher or lower than costs calculated for the example.

Finally, the Summary section discusses the advantages and limitations of the technology, based on information presented in the above sections, and provides an overall evaluation of the technology for application at uncontrolled hazardous waste sites.

C. Containment Technologies

1. Groundwater Barriers

DESCRIPTION

Groundwater barriers are designed to prevent the off-site migration of contaminated groundwater by physically restricting groundwater flow. They can also be used to enhance the performance of other remedial technologies. For example, a barrier can be placed slightly down gradient of a groundwater pumping system at the edge of a plume. The barrier serves to halt the movement of the plume, and minimizes the quantity of uncontaminated water available for pumping. The five major types of groundwater barriers are:

- o slurry walls - fixed underground physical barriers formed by pumping slurry into a trench as excavation proceeds and either allowing the slurry to set (for cement-bentonite) or backfilling with a suitable engineered material (for soil-bentonite). Slurry walls are the most widely used groundwater barrier. Figure 1 shows a typical slurry wall construction;
- o grout curtains - fixed underground physical barriers formed by injecting grout, either particulate (such as portland cement) or chemical (such as sodium silicate), into the ground through well points. A typical grout curtain is shown in Figure 2;
- o pilings - fixed underground physical barriers constructed by driving webbed sections of sheet pilings (typically steel) into the ground. Each section is connected with interlocking socket or bowl and ball joints which soon fill with fine-medium grain soil particles to restrict groundwater flow through the barrier. Typical sheet piling section profiles are shown in Figure 3;

FIGURE 1
CONSTRUCTION OF A BENTONITE SLURRY WALL
 (Source: Sommer and Kibben, 1960)

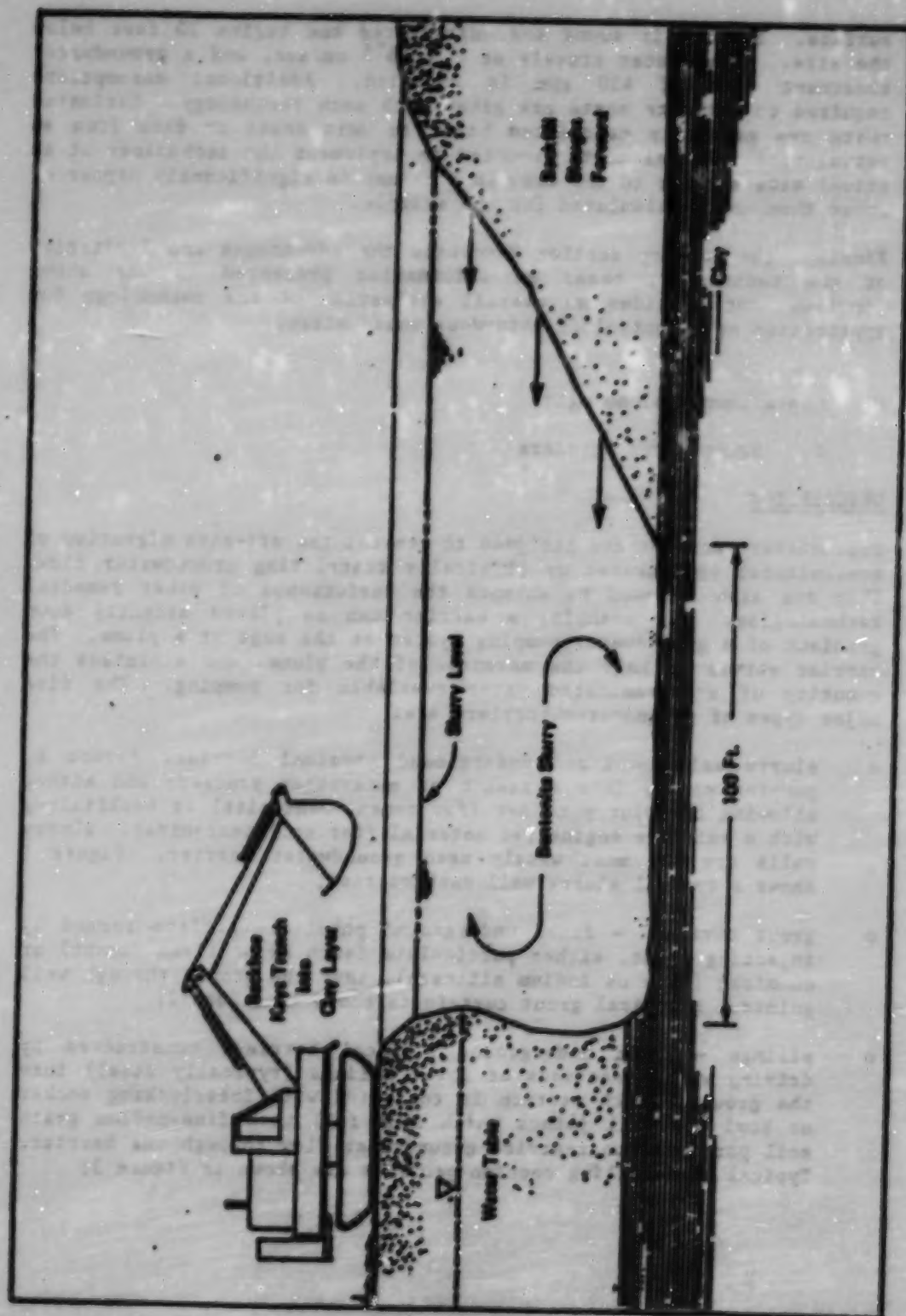


FIGURE 2
SEMICIRCULAR GROUT CURTAIN AROUND UPGRADIENT END OF LANDFILL
(Source: EPA, 1982)

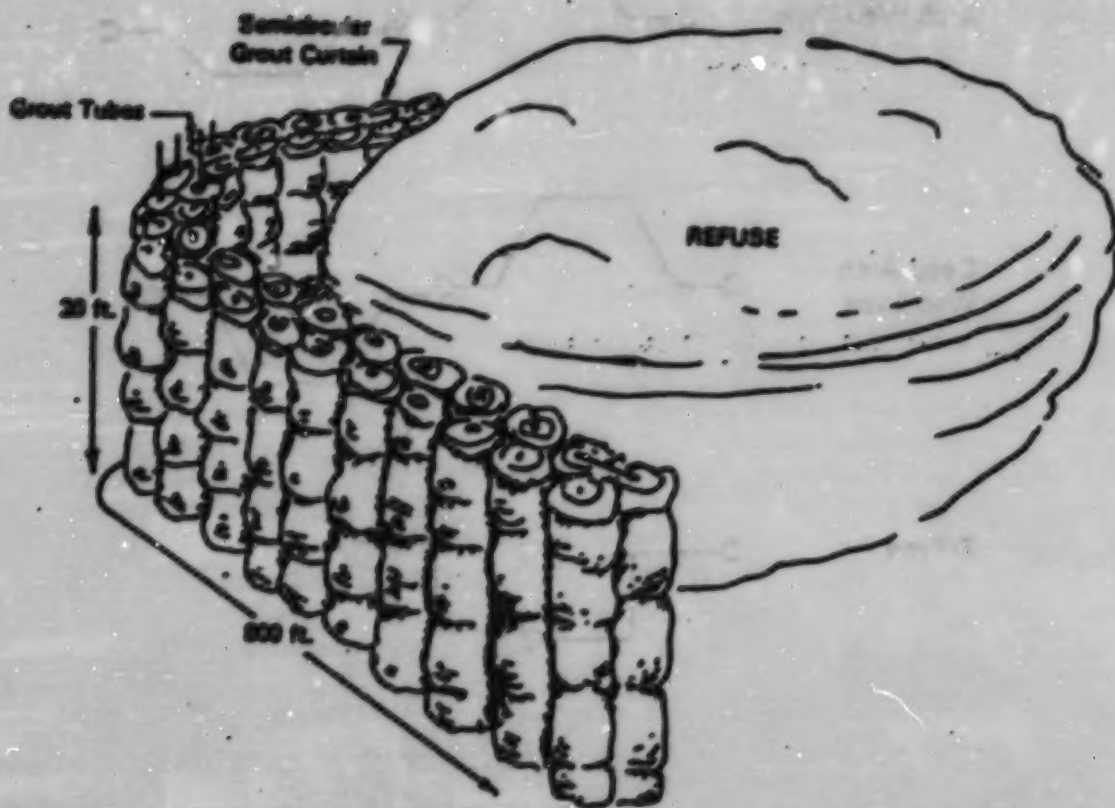


FIGURE 3
SHEET PILING SECTION PROFILES
(Source: EPA, 1982)

Straight Web Type



Arch Web Type



Deep Arch Web Type



Z-Type



Y-Fitting

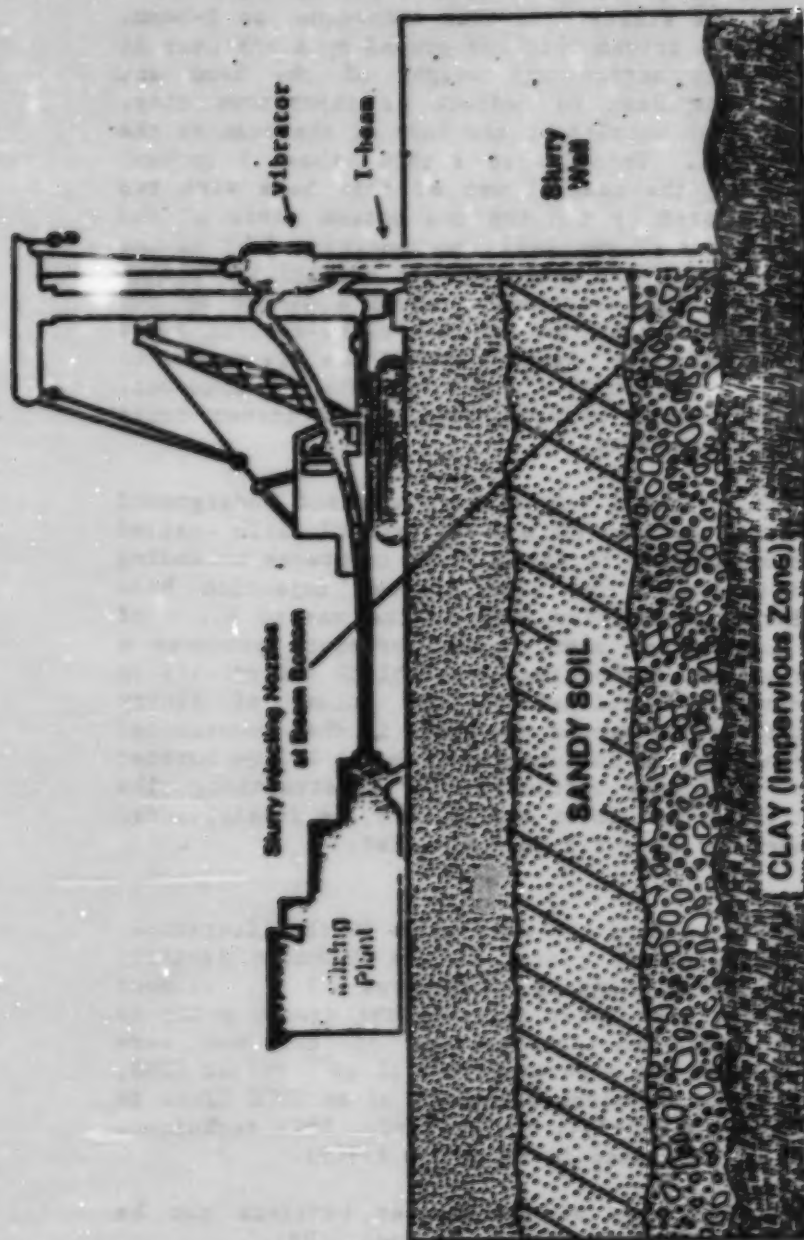


T-Fitting

- o vibrated (or vibrating) beam - a means to construct a slurry wall using a vibrated beam in place of a clam shell or backhoe to provide a channel for the slurry. In this technique, an I-beam, suspended from a crane is driven into the ground by a vibrator at its top. The vibrating action and weight of the beam and vibrator drives the beam down to bedrock or impervious clay. Slurry is injected through nozzles at the base of the beam as the beam is slowly withdrawn. This leaves a thin (about 3 inches) section of slurry along the central web of this beam with two perpendicular parts created by the top and bottom parts of the beam. Succeeding sections of the wall are constructed by moving the beam in the direction of the wall but with sufficient overlap to provide continuity. Figures 4 and 5 shows a sketch of the beam and also a view from the top of the cross-section of a typical section of slurry wall. Special techniques are needed to insure that beam is very carefully aligned with the previous cut. Deviations from the vertical of more than a few inches could leave gaps in the wall (windows).
- o block displacement - a method for placing a fixed underground physical barrier around and beneath a large mass of earth (called a block). The bottom barrier is formed when fractures extending from horizontal notches at the base of the injection hose coalesce into a larger separation beneath the massed block of earth. Continued pumping of slurry under pressure produces a large uplift force against the bottom of the block and results in vertical displacement proportional to the volume of slurry pumped. A perimeter barrier around the block is then constructed by conventional techniques in conjunction with the bottom barrier either prior to or following bottom barrier construction. The block displacement technique, shown in Figure 6, is developmental and its effectiveness is currently being studied.

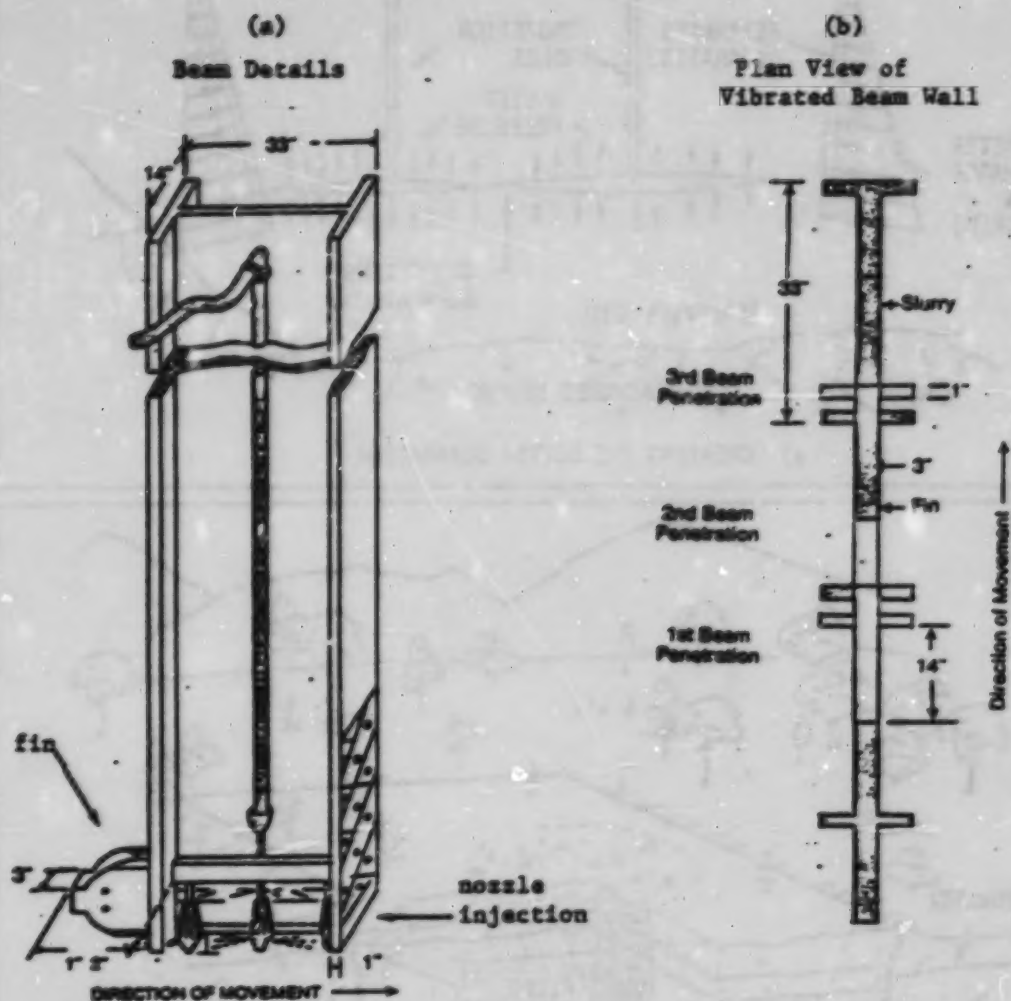
Two other groundwater barrier techniques were found in the literature. The first was a mud filled trench placed at the Richmond Sanitary Landfill. Conventional trench digging procedures (i.e., without slurry) were used. Problems with water entering the trench prior to backfill placement and with moisture content of the mud were encountered. The mud backfill had a permeability of 10^{-8} cm/sec (JRB, 1984, p. 20-16ff). The second involves placement of an HDPE liner in a trench which is subsequently backfilled with sand. This technique, called an "enviro-wall," is discussed in Salvatore (1983).

Additional descriptive information on groundwater barriers can be found in EPA, 1982; EPA, 1984; and Ehrenfeld and Bass, 1983.



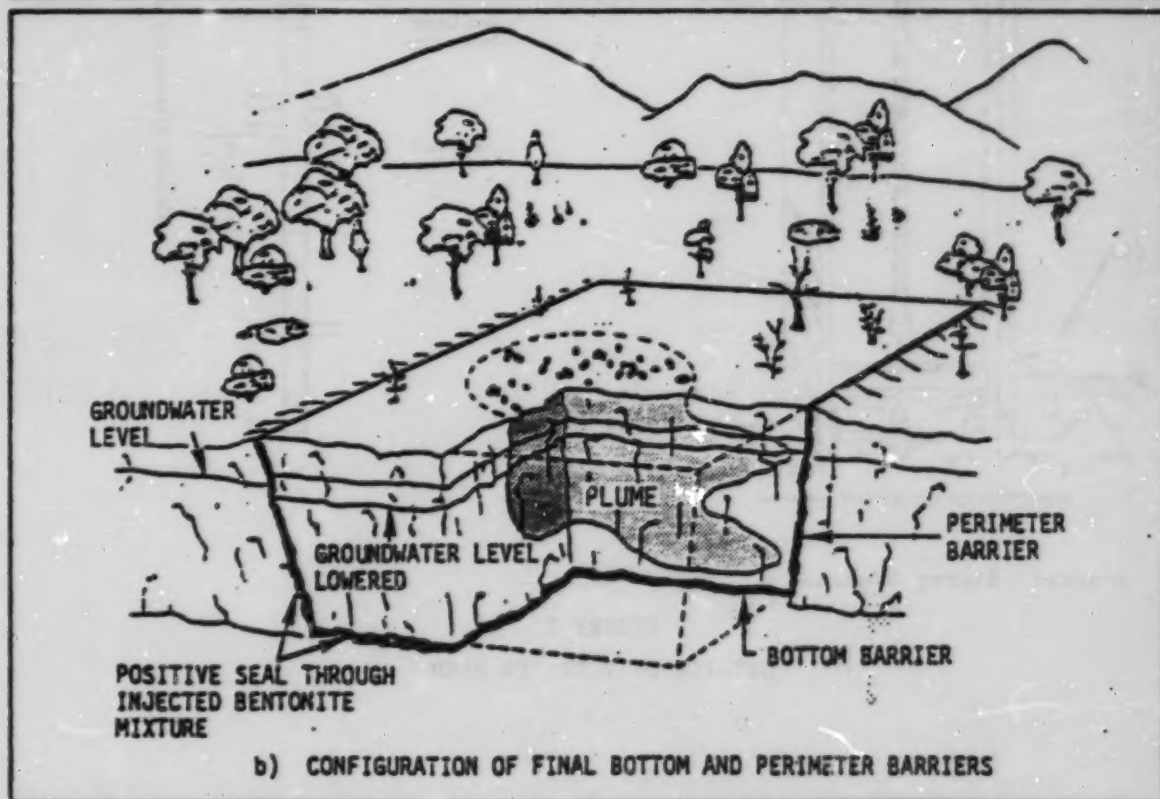
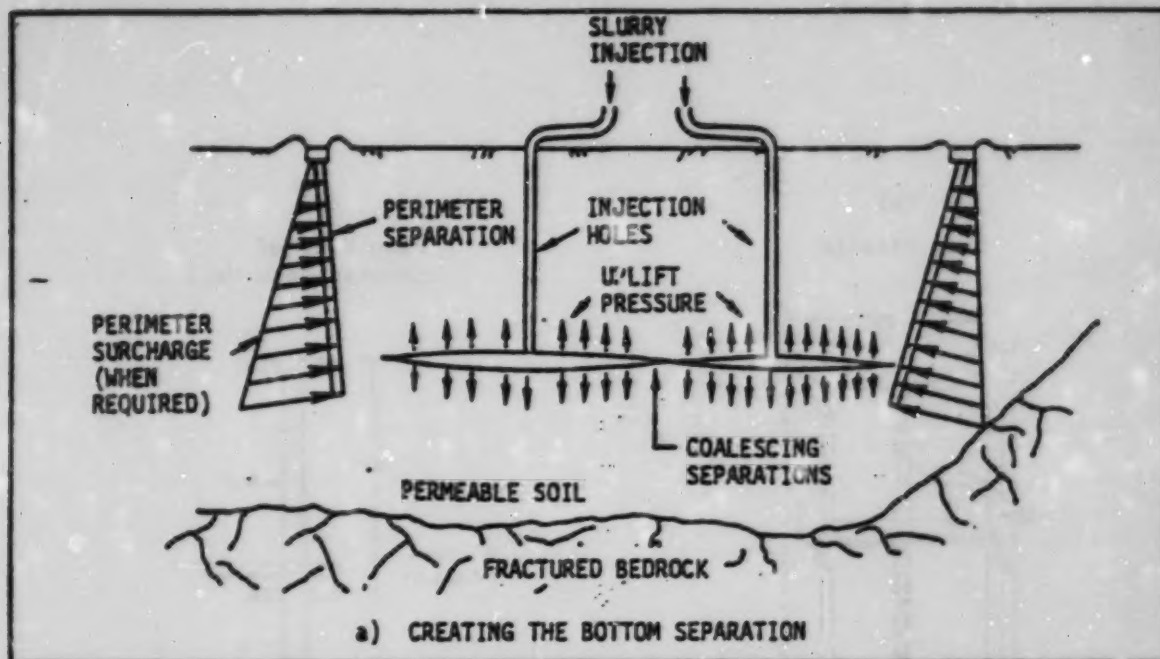
Source: Slurry Systems

FIGURE 4
SCHEMATIC DIAGRAM OF VIBRATED BEAM SYSTEM



Source: Slurry Systems

FIGURE 5
DETAILS OF VIBRATED BEAM



Source: Ehrenfeld and Bass, 1983

FIGURE 6
BLOCK DISPLACEMENT METHOD

CAPABILITY

Range of Applicability

Groundwater barriers were used at 5 of the 23 sites discussed in JRB, 1984. Slurry walls are the most commonly used groundwater barrier technique. Experience with vibrating beam and grout curtain techniques in hazardous waste site applications is less common. No experience has been identified with the use of sheet piling at hazardous waste sites, and block displacement has been pilot tested at only one site.

Chemical compatibility of the groundwater barrier with waste constituents varies depending on the specific materials used. Various types of slurry, backfill, grout and piling materials are available. Chemical compatibility testing should always be performed in selecting materials for a specific application. General chemical compatibility information can be found in EPA, 1982; EPA, 1984; and Ehrenfeld and Bass, 1983.

Groundwater barriers generally must be keyed into an impermeable layer, such as bedrock or clay layer, beneath the site to be fully effective. A mathematical demonstration of this principle is given in Knox, 1983. Other site-specific requirements for each type of groundwater barrier are given in Table 2.

Barrier applicability may be increased by using a combination of techniques. Grouting, for example, might be applicable to help tie a barrier to fractured or weathered bedrock. Combinations of barrier techniques may also be used when site conditions change along the line of the wall. An example of this is the Stroudsburg site (JRB, 1984, 18) where a grout curtain was used instead of a slurry wall along part of a dike since trenching required for the slurry wall would threaten the structural integrity of the dike.

Effectiveness

Groundwater barriers are not, as they are sometimes referred to, impermeable barriers. Rather, they are low permeability barriers. Typical design standards for groundwater barriers are on the order of 10^{-8} centimeters per second. This standard means that 77 gallons/year of groundwater would pass through a barrier which is 10 feet deep by 100 feet long. For each order of magnitude that the permeability is increased, the amount of liquid passing through the barrier increases by a factor of 10. If used alone groundwater barriers would, thus, permit some movement out of or into the contaminated region, depending on the hydraulic gradient. By controlling the gradient with pumps or drains, the direction of flow can be kept inward so that no contamination will migrate from the site as long as all components continue to function properly.

TABLE 2

SITE CONSIDERATIONS FOR GROUNDWATER BARRIERS

	<u>Max. Depth to Impermeable Layer</u>	<u>Soil Conditions</u>	<u>Equipment Access</u>
Slurry Wall	45 ft. w/backhoe, 72 ft. w/special backhoe, deeper w/clam shell	must be able to be excavated	backhoe or clamshell
Grout Curtains	-	<20% pass No. 200 Sieve	drilling rig
Sheet Pile	30 ft	loosely packed, <10 blows/ft recommended	crane
Vibrating Beam		no large obstacles, e.g. rocks, boulders	crane to support beam
Block Displacement	N/A	limited	backhoe, drilling rig

The three major technical uncertainties for groundwater barriers are: chemical compatibility, continuity, and ability to key into bedrock (except for block displacement). Chemical compatibility is important since chemical attack may increase the permeability of the barrier. Compatibility testing is generally required before the barrier is placed, but these are short term tests using an expected range of contaminants. The presence of unexpected contaminants and longer term exposure can reduce the usefulness of the barrier. The barrier may become more permeable to concentrated contaminants, such as solvents present in separate phases, than to groundwater containing very dilute dissolved organic species.

Continuity is also important for all of the techniques. For grout curtains, vibrating beam and block displacement this means physical continuity, since it is impossible to verify that the grout curtain, thin vibrating beam wall or bottom barrier under the displaced block is continuous at depth. For slurry walls, continuity means the uniformity of the slurry or backfill in meeting design requirements. For sheet piles, continuity means the effectiveness of the joints to restrain groundwater flow. In all cases, careful quality control and quality assurance is necessary to increase the probability that the wall is in fact continuous. Specific QA/QC techniques developed for each type of barrier decrease the technical uncertainty of implementing the technology, but experience is still lacking to verify their success.

Finally, each type of barrier, except for block displacement, must be keyed to an impermeable layer. It has been demonstrated in practice and in theory that a barrier is not effective if contaminants can flow beneath the barrier. Barriers must, therefore, be tied into an impervious layer such as bedrock or clay. This is of particular concern for grout curtains, sheet piles and vibrating beam barriers where actual excavation of the impervious layer does not occur. In addition, the quality of the impervious layer must be such that contaminants are not transported through the layer. Tying a slurry wall into fractured bedrock, for example, does not provide the necessary level of containment. These technical uncertainties can be reduced through material selection, technology selection and careful construction practices.

These technical uncertainties are highlighted by two case examples. At the first, the Stroudsburg site (JRB, 1984, 18), monitoring data indicate the slurry wall and grout curtain installed are controlling seepage through a dike and the lateral movement of contaminated groundwater. However, there is considerable concern that other discharge locations are possible and that vertical migration of contaminants may be occurring. The City of Stroudsburg drinking water comes from a water supply which is 700 feet deep and downgradient from the site. Additional studies are planned to determine whether the barrier is effective in controlling the migration of contaminants to the aquifer or whether other remedial measures may be required. In the second example, a vibrating beam barrier at Anonymous Site A (JRB,

1984, 1), appears to be functioning according to design. This is based on visual observation (seepage control) and the performance of an exposed "test" section of the barrier. There is, however, no groundwater monitoring data available which would verify the continuity of the wall at depth and its effectiveness in controlling contaminant migration.

The secondary effects of groundwater barriers are minimal. Slurry walls involve the excavation of contaminated soil which can cause health problems and the need for offsite disposal if the excavated soil is not used in the backfill. In addition, some grout materials may be health hazards and indeed may themselves cause groundwater contamination problems. Use of toxic grouts or other hazardous materials for groundwater barriers should be avoided.

Reliability

The short-term usefulness of groundwater barriers has been demonstrated at several sites including the two noted above. There are currently little data, however, to verify the long-term reliability of the technologies. The barriers in the examples given above were installed in 1982 and groundwater barriers have generally not been in place long enough in hazardous waste site applications to assess long-term effectiveness. Long-term experience with groundwater barriers may be available from the construction industry since barriers are commonly used in site dewatering. This experience, however, would not be relevant to hazardous waste sites since chemical compatibility is generally not a problem at construction sites, and water exclusion rather than containment of contaminants is the primary concern. Seepage rates through the barrier which are acceptable at construction sites may be of concern in hazardous waste site applications. No real problems with groundwater barriers beyond the technical uncertainties described above were identified in the literature.

RESOURCE REQUIREMENTS

Costs

- o Slurry walls - Capital costs are generally given in dollars per square foot. Under the best conditions and using a backhoe, costs may be as low as \$2-3/ft². When a clamshell is required for excavation, or if other factors make excavation more difficult, costs may exceed 10/ft². Capital costs at the Stroudsburg site (JRB, 1984, 18) were about \$30/ft². Costs exceeded the planned amount by about 40%. No operation and maintenance is required other than monitoring.

- o Greet curtains - Capital costs include soil groutability testing, equipment mobilization, and grout. Volume of grout required is a function of the area of the wall, number of rows, and porosity of the soil. Most grouts cost from \$1-3/gallon, although some may be significantly more expensive. No O&M is required other than monitoring.
- o Piling - Capital costs are on the order of \$750 to \$850/ton (15-25 ft sections of galvanized steel) including installation costs. Unit cost is \$9-14/ft², depending on depth (Godfrey, 1983). Barrier area is calculated as length times depth times 1.6 to account for interlocking of the piles (EPA, 1982). No O&M is required other than monitoring.
- o Vibrating beam - Capital costs are comparable to slurry walls. Site preparation may increase costs significantly. At Anonymous Site A (JRB, 1984), widening the dike to provide access to the crane suspending the vibrating beam increased the cost from about \$8/ft² to \$17/ft². No O&M is required other than monitoring.
- o Block displacement - No data are available since the technique is developmental.

Personnel

Additional personnel may be required to provide QA/QC for vibrating beams to make sure beam stays vertical.

Example

An impermeable barrier around the entire plume would be 2400 feet long and 20 feet deep.

- o slurry wall or vibrating beam: \$250,000
- o grout curtain: \$1,250,000
(two-row, 3 foot centers, 30% porosity)
- o piling: \$300,000

SUMMARY

Groundwater barriers have become one of the principal options for plume containment at clean-up sites. They may be used alone, but often are employed in combination capping or groundwater pumping. All, except block displacement, are derived from general construction practices and have been demonstrated to be effective under a wide range of conditions. Experience under conditions at clean-up sites is as yet limited, and there are little data available as to the long-term effects of contaminants in the groundwater that contact the

barrier. Special construction techniques may be required because the hazardous materials present pose risks to field crews not found at conventional construction sites.

These systems must key into bedrock to be effective over the long run. They are limited to sites where bedrock is not extensively fractured or is not too deep for the chosen technique.

None of these techniques, alone, provides a completely impermeable barrier even if constructed ideally. But with some ancillary system to contain the leakage or dewater the zone within the barrier, contamination which would otherwise continue to migrate away from the original site, albeit at very low rates, would be contained. The ancillary system would have to function indefinitely.

Alternatively, combinations of barriers with treatment of groundwater and contaminated soils contained within the barriers could, however, achieve an essentially permanent solution in a finite period. The barriers are needed to contain the wastes during the several years it may take to carry out the treatment.

2.2 Groundwater Pumping

DESCRIPTION

Groundwater pumping uses a series of wells to remove groundwater for treatment or to lower the water table to contain a plume. A well point system, consisting of a series of riser pipes screened at the bottom and connected to a common header pipe and a centrifugal pump is used in shallow aquifers to a depth up to 10 meters. Deep well systems, which can be pumped at higher rates than well point systems, may be effective to depths up to several hundred meters. A schematic of a well-point dewatering system is shown in Figure 7.

Additional descriptive information on groundwater pumping systems may be found in Freeze and Cherry, 1979; EPA, 1982; and Ihrenfeld and Bass, 1983.

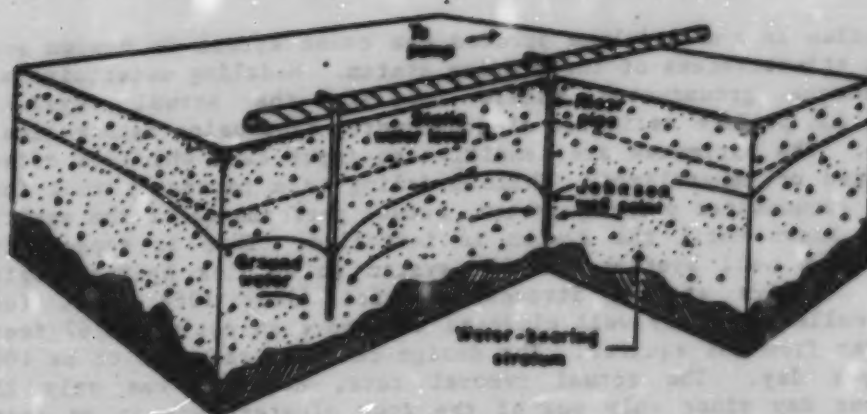
Range of Applicability

Groundwater pumping was used at 6 of the 23 sites discussed in JRB, 1984. Pumping can be used to contain a plume or as part of a treatment system to remove contaminants from an aquifer. Techniques for groundwater pumping are well developed and depend on standard technology.

The applicability of groundwater pumping to a site depends on site specific factors, and on the purpose of the groundwater pumping system. If groundwater pumping is used to contain a plume, aquifer characteristics and the location of contaminants must be such that they can be controlled by pumping. An example of this is a site in

new land use is a critical consideration in the design of a dewatering system. It is essential to understand the hydrogeology of the site, including the location and depth of the water table, the permeability of the soil, and the presence of any underlying rock formations. The design of the dewatering system should take into account the potential for contamination of the water table and the need to maintain a safe water level in the area. The system should be designed to be flexible and adaptable to changing conditions over time.

FIGURE 7
SCHEMATIC OF A WELL POINT DEWATERING SYSTEM
 (Source: EPA, 1982)



New York where a hydraulic containment system is used to lower the groundwater table to prevent reentrainment of oil from the unsaturated zone. If pumping is used to remove contaminants from the aquifer, the location of the wastes relative to the water table, waste characteristics, the extent of the plume and other site factors must be considered. The pumping system must be designed based on these considerations. The pumping system at the New York site, for example, does not remove contaminated oil from the unsaturated zone. Recharge of pumped groundwater in areas with unsaturated zone contamination, however, could serve to flush the contaminated oil from the soil, thus allowing the system to remove the oil. Groundwater modeling is often used to determine the best design and expected effectiveness of a groundwater pumping system.

Effectiveness

Groundwater pumping is capable of containing a plume indefinitely and treating a contaminated aquifer to desired levels. The effectiveness of a groundwater pumping system depends primarily on how well it is designed. For a shallow well point system in an unconfined aquifer to contain a plume, little deviation from design performance would be expected. In a more complicated situation, however, such as a deep well aquifer treatment system in a glaciated area, the technical uncertainties are higher.

Uncertainties in the modeling process can cause errors in design and estimated effectiveness of the pumping system. Modeling uncertainties arise because groundwater models simplify the actual physical processes and produce estimates of groundwater flow using mathematical equations. The estimates are sensitive to input data which is often hypothesized or generalized. While modeling is a necessary tool for designing groundwater pumping system, actual performance of the system cannot be known until the system is installed. This is especially true for deep well systems and for system in complex hydrogeologic settings. Design at the Stroudsburg site (JES, 1984, 18), for example, called for four well clusters to remove an estimated 67 feet of coal tar from the aquifer. The design recovery rate was to be 100 gallons per day. The actual removal rate, however, was only 25 gallons per day since only one of the four clusters was in an area where coal tar could actually be pumped from the aquifer. Monitoring data are required to verify the effectiveness of the pumping system. Performance of groundwater pumping at Goose Farm (JES, 1984, 11) and Howe, Inc. (JES, 1984, 14) was not evaluated due to lack of existing monitoring data from the sites.

Secondary effects of groundwater pumping involve the need to treat contaminated groundwater prior to discharge. In addition, groundwater levels may be a problem at sites where maintenance of a constant groundwater level is important or required by law.

Reliability

Although little actual data are available to assess the long-term performance of groundwater pumping systems, reliability is expected to be high. This is due to the fact that the system does not change significantly over time. Problems which may be encountered include failure of mechanical equipment and physical clogging of the well screens. Neither of these problems is serious, and both can be easily corrected. Short periods of down time do not affect the performance of a groundwater pumping system since groundwater flow rates are generally slow. For a groundwater pumping system to perform reliably, however, is it important that the system be well designed from the start and that monitoring data be available to assess system performance. Without monitoring data, the system will not be adjusted as required to maintain reliability.

RESOURCE REQUIREMENTS

Costs

A preliminary study, including groundwater modeling, will generally be required to design a groundwater pumping system. For example, at the Occidental Chemical site (JES, 1984, 17), \$175,000 was spent on modeling prior to design and construction of a \$1.56 million pumping system. At the Stoudsburg site (JES, 1984, 18), \$130,000 was spent on preliminary studies prior to installation of a \$150,000 pumping system. Preliminary study and modeling costs will depend on the complexity of the problem, including the type of model required.

Capital costs depend primarily on the number and depth of the wells. Cost for well installation varies significantly depending on drilling techniques, hole diameter, material used, and difficulties encountered. A typical range is \$20-40 per foot of well installed. Costs for pumps and pipe (to transfer water from the wells or wellpoints to treatment or discharge) may also be significant. A 4-inch submersible pump rated at 23 gpm, for example, costs \$1600. Typical cost for PVC pipe is \$15/ft.

Operation and maintenance costs include electricity and pump maintenance. These costs are negligible compared to the overall cost of the system. The continuing costs of any type of treatment system, if used in conjunction with the pumping system, will generally dominate the costs of the pumping portion.

Personnel

No special requirements.

Example

Groundwater pumping at the example site involves 18 PVC well points spaced 15 feet apart along the leading edge of the plume. Each well is pumped at 25 gpm using 18 submersible pumps. 1250 feet of additional piping is required to transfer water to an onsite treatment system. Total capital cost for the system would be \$55,000 to \$65,000.

SUMMARY

Groundwater pumping is expected to be an effective and generally inexpensive method for removing contaminated groundwater for treatment or disposal, especially when used in conjunction with groundwater barriers. It can also be effective in reversing groundwater gradients to contain a plume. Pumping offers a high design flexibility (number of wells, location, depth, pumping rate, etc.) to meet a wide variety of site-specific requirements. The technology is proven and is quite reliable. The main constraint is that the system be well designed. Uncertainties associated with groundwater modeling, especially in complicated flow regimens and for deep well systems, necessitate that the effectiveness of the system be verified in the field. The system can then be modified as required by changing flow rates or adding additional wells. These modifications, however, may reduce the cost-effectiveness of the system.

Groundwater pumping systems may be operated for potentially long periods of time. As soon as the system is shut down, groundwater flow patterns will return to their pre-pumping condition. When pumping to contain a plume, therefore, the pumps must be operated indefinitely or until the contaminants in the plume are degraded through treatment or natural processes. When pumping to treat contaminated groundwater, contaminants in the unsaturated zone must be considered. If the pumps are shut down when the pumped groundwater meets the applicable standards the groundwater table will rise and may re-entrain contaminants previously in the unsaturated zone. Groundwater pumping, therefore, may be effective in the long term only if the source of contamination is also contained or treated.

3. Subsurface Drains

DESCRIPTION

Subsurface drains are constructed by placing tile or perforated pipe in a trench, surrounding it with gravel (or similar material), and backfilling with topsoil or clay. Subsurface drains can be installed to collect leachate as well as lower the water table for site dewatering.

Additional descriptive information on subsurface drains can be found in EPA, 1982 and Ehrenfeld and Base, 1983.

CAPABILITY

Range of Applicability

Subsurface drains were used at 6 of the 23 sites discussed in JRB, 1984. Drains are applicable to shallow contamination when the contaminants move with the groundwater flow. They are used primarily for the same purpose as well point systems, but are more effective in low permeability and/or heterogeneous soils. They also may be more effective for large plumes due to their large zone of influence. Drain systems are more applicable to floating and/or low viscosity contaminants.

Effectiveness

Subsurface drains are capable of collecting contaminated groundwater for treatment or of changing the direction of groundwater flow to contain a plume. An example of the latter application is the G.E. site in California (JRB, 1984, 9) where three drains were designed to reverse the gradients and contain a plume of PCB-contaminated oil in the groundwater.

Technical uncertainties associated with subsurface drains are those associated with predicting groundwater flow. Design uncertainty will be a function of the quality of information available to the designer and the complexity of the groundwater flow regime. The technology itself is straightforward and does not introduce its own uncertainty to the situation. Technology effectiveness is, however, dependent on the design of the subsurface drain, including configuration, depth, and spacing.

A primary secondary effect associated with subsurface drains is that contaminated groundwater which is collected must be treated or otherwise disposed of. In addition, excavation of contaminated soils may be required.

Reliability

The short-term effectiveness of subsurface drains depends on its ability to establish the design zone of influence. At two sites, the G.E. California site (JRB, 1984, 9) and Anonymous Site D (JRB, 1984, 2), water level data indicate that a zone of influence was successfully established. Data at the G.E. site also suggest that groundwater flow reversal was attained, thereby containing the plume. Data to verify the long-term effectiveness of subsurface drains, however, in collecting or containing contaminated groundwater is lacking. At the six sites with subsurface drains discussed in JRB, 1984, only one, Anonymous Site C, had groundwater monitoring data

available. Monitoring data at Anonymous Site C, which are reported quarterly to the Wisconsin Department of Natural Resources, show no indication of chromium reduction at the site, and indicate that a long time may be required for chromium reduction to occur. Even at this site, however, there are not enough data to determine if the contamination is being contained by the system.

Subsurface drains must be monitored and maintained to avoid problems with system clogging. A subsurface drain at the Chemical Recovery Systems, Inc. site (JRB, 1984, 6) failed in 1976 due to clogging attributed to inadequate design. Not enough coarse material was placed over the pipe to prevent fines from clogging the system. This drain was then replaced by a new drainage system which also has experienced some problem with sedimentation. The new drain must be cleaned periodically with standard sewer cleaning equipment to maintain system performance.

The long-term effectiveness of subsurface drains is also limited by the fact that only contaminants which flow with the groundwater are available to the system. Immiscible materials, such as PCB-contaminated oil, will exist in several phases, including oil in the unsaturated zone, oil in the capillary fringe, and oil which will flow freely with groundwater. Fluctuations in groundwater levels cause the amount and location of free-flowing oil available to vary with time. It would therefore be very difficult to remove a large percentage of the oil with a drainage system alone. This is especially true if the site is capped, such that surface water is not allowed to infiltrate to flush out oil from the non-free-flowing zones. The physical characteristics of the system, therefore, require that a subsurface drain operate continually to contain the plume until the contaminants are degraded through natural processes. If at any point the system is removed or ceases to function, contaminants will be free to migrate with the groundwater. The same problems would occur for well point systems used to control floating contaminants. This situation is occurring at a site in New York State.

RESOURCE REQUIREMENTS

Costs

Installation costs are the most significant costs for subsurface drains. At Anonymous Site B (JRB, 1984, 2), for example, the subsurface drainage system cost \$207,000. \$197,000 of this cost was for trench installation. At the GZ site (JRB, 1984, 9) installation costs were \$337,000 for about 210 feet of trench. At Anonymous Site C, on the other hand, a 240 foot long trench cost only \$8000 to install.

As seen above, unit costs for subsurface drains vary significantly depending on site specific conditions (including construction technique and problems encountered). Unit costs above are \$800/linear foot, \$1600/linear foot and \$33/linear foot, respectively (amounts shown are for trench installation only and do not include material costs). It is not clear, from the information in the references, what causes the very large variations. The more expensive installations were deeper than the cheapest, but not so much as to cause the very large difference. Costs reported in the literature are on the order of \$40-50 per linear foot for installation and materials.

Personnel

No special requirements.

Example

At the example site a 200 foot long subsurface drain may be used to intercept the plume. The drain would be 20 feet deep using a 12" PVC pipe surrounded by gravel. The top of the trench is backfilled with 5' of clay. Total installed cost for this system, including sump and two 25 gpm pumps, is estimated (based on literature values) to be \$15,000 to \$20,000 installed. Alternatively, using actual unit costs from the GE site, however, the estimated costs for this system would be much higher, about \$330,000.

SUMMARY

Subsurface drains is a very old technology, proven under an extremely wide range of conditions. In general, drains are relatively inexpensive to install and have low O&M costs. Costs, however, will vary depending on site-specific conditions.

Drains compete with wells where soils are heterogeneous or exhibit low hydraulic conductivity, or where the contaminated plume is very large. They may be preferred to wells where there is a contaminant layer floating on the groundwater or where the contaminants are quite viscous. They are not as versatile as wells, however, and are more sensitive to design errors.

Placing drains in highly contaminated soils may require special construction techniques.

Drains are susceptible to clogging and to variations in groundwater flow and level. Contaminated groundwater collected must be treated or disposed.

4. Run-On/Run-Off Controls

DESCRIPTION

Surface water control technologies are designed to prevent contaminated surface water from leaving a site, and uncontaminated water from entering a contaminated area. Run-on/run-off control technologies include dikes, terraces, channels, chutes, downpipes, grading, and revegetation. Detailed descriptive information on these technologies, with diagrams, can be found in Ehrenfeld and Bass, 1983 and Freeze and Cherry, 1979.

CAPABILITY

Range of Applicability

The applicability of surface water control technologies depends entirely on site factors and is independent of waste specific factors. Important site factors include topography, erosion potential, surface water flow patterns and expected rainfall (including precipitation from a design storm).

Surface water control technologies are generally used to complement the function of more basic remedial action techniques such as surface seals or excavation and removal.

Effectiveness

Surface water control technologies should be effective in controlling surface water at a site. Design and construction is very straight forward and results are readily observable. The only potential uncertainty is that maintenance may be required for the technique to function over time. Many of the techniques involve the use of temporary earthen structures, such as dikes, which can be eroded by surface water flow. Stabilization with vegetation or soil additives is required to maintain the structures. In addition, all earthen structures should be inspected after storms. The only secondary effects associated with surface water control technologies is that contaminated runoff may require treatment prior to discharge.

Reliability

Short-term reliability of surface water control technologies should be high since the technologies are standard practice and the results are observable. Long-term effectiveness should be high if the system is properly maintained.

Examples from JRB, 1984, of surface water control at remedial action sites are a berm constructed of excavated soil at Anonymous Site C to direct surface water away from the surface impoundment, a diversion ditch constructed at the Fairchild Republic site to protect excavation areas from surface runoff, drainage channels and various other surface water control techniques used at a General Electric site, and surface water controls at the Mauthe site as temporary measures to protect from storm flooding.

RESOURCE REQUIREMENTS

Costs

The costs for runoff/runoff technologies are generally small compared to other costs at a cleanup site. Data on the cost for surface water controls for the examples given above are not available but are expected to be significantly less than the cost for major remedial actions performed at the sites. The major cost element for runoff/runoff controls is labor for initial construction, inspection and maintenance, and periodic reconstruction as required.

Personnel

Design personnel required for runoff/runoff controls are less for other technologies since only a conceptual design is required. Personnel requirements for inspection and maintenance may be greater than for other technologies since inspection is required periodically (e.g., weekly) and after storms.

Example

At the example site a 500 foot dike and diversion ditch is required up slope of the disposal area to protect the site from surface runoff. Total cost for construction of this system, including stabilization with grass, is \$1,000.

SUMMARY

Surface water controls are almost always employed in conjunction with other technologies. They reduce the opportunity for infiltration or runoff. They use conventional, widely applied, inexpensive techniques. Maintenance is required for continued effectiveness and regular inspections may be necessary, especially following major storm events.

5. Surface Seals/Caps

DESCRIPTION

Surface seals are low permeability barriers placed over a site to reduce surface water infiltration, control erosion, contain and control gases and odors, and/or provide a surface for vegetation and other post-closure uses. Various low permeability materials may be used, including soils and clays, admixtures (e.g., asphalt and concrete, soil cement), and polymeric membranes (e.g., flexible membrane liners). Typical surface seals are shown in Figure 8.

Additional descriptive information on surface seals can be found in EPA, 1982; Ehrenfeld and Bass, 1983; and Lutton, 1980.

CAPABILITY

Range of Applicability

Surface seals/caps were used at 9 of the 23 sites discussed in JRB, 1984. They were used both as interim measures and as long-term remedial actions. A cap was used as an interim measure at a site in New Jersey where asphalt was placed over the entire site to control the dispersion of, and avoid direct contact with, mercury contaminated soil. An example of capping as a long-term remedial action is the Sylvester site in New Hampshire where a 20 mil PVC cap was placed, covered with soil, and revegetated to control infiltration. At this site the cap was used in conjunction with a slurry wall and groundwater treatment.

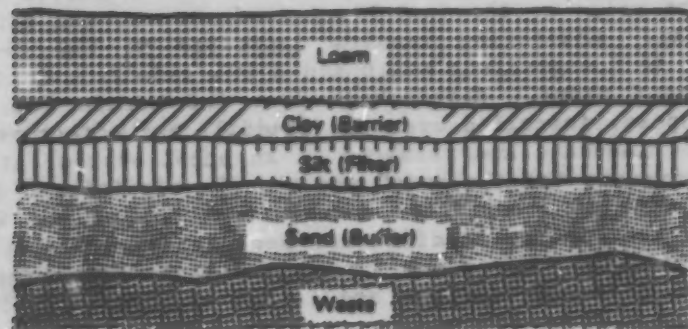
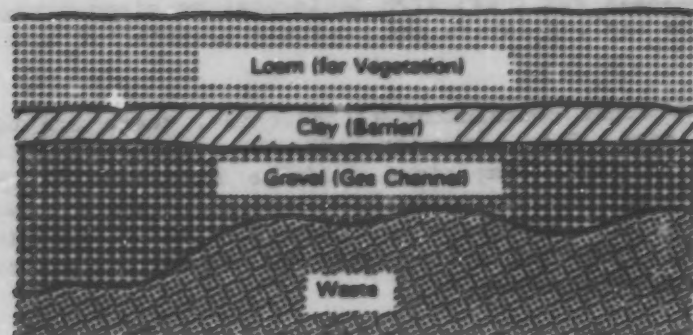
Caps are generally applicable to any site where infiltration of groundwater, dispersion of surface soils, or odors are a problem. Waste factors (e.g., location, volatility) may be important in determining design requirements for the cap. Site factors which must be considered include topography, site accessibility and the presence of large structures or trees.

Effectiveness

Caps are theoretically capable of preventing the infiltration of surface water, and of providing complete control for dispersion of surface contaminants and odors. They must be properly designed, installed and maintained to be effective. At the Mountain View site (personal communication, J. Johnson), for example, a 6 inch soil cap failed due to water erosion. Caps are usually well drained and covered with aggregate material or covered with soil and vegetated to prevent erosion. In another case, an asphalt cap at the Chemical Metals Industries site (JRB, 1984, 5) was subject to cracking due to installation in cold weather. The on-scene coordinator decided to install the cap in winter, against the advice of the contractor, in order to provide short-term protection for the site. Cracks which occurred the following summer then had to be repaired.

FIGURE 8

TYPICAL SURFACE SEALS
(Source: Lutton, 1980)



There are generally no secondary effects associated with capping alone. The effects of capping on other remedial technologies, however, must be considered. At the Rocky Mountain Arsenal, for example, it was decided that capping would reduce the effectiveness of groundwater pumping since reducing infiltration would also reduce the amount of water available to flush the aquifer. Capping may also reduce the natural degradation of contaminants near the soil surface by limiting aeration (for biodegradation) and restricting sunlight (for photolysis).

Reliability

As noted above, the integrity of a cap can be destroyed by cracking due to the freeze-thaw cycle. In addition, cracking can be caused by drying and settling as the waste shifts and undergoes changes. Burrowing animals and roots from accidental or planned vegetation may penetrate the sealing layers and create a channel for water and vapor flow.

As with most other containment technologies, there are only limited monitoring data for assessing the long-term effectiveness and reliability of caps. Empirical evidence from most sites indicates that, as long as they are properly maintained, caps are performing as designed and are effective in reducing or eliminating surface infiltration. Long-term reliability will depend in part on effective inspection and maintenance.

Monitoring data are available for the cap used to close the Windham Landfill in Connecticut. The cap consisted of a regraded subbase, 10 centimeters of sand, a 20 mil PVC liner and 46 centimeters of sand and gravel which was also vegetated. The site was monitored extensively for 14 months prior to the installation of the cap and for 26 months since capping. Monitoring results indicated an 80% reduction in contaminants in downgradient wells and a 30% reduction in the size of the contaminant plume. Researchers from SMC Martin Inc. concluded that "the topsoil installed over the landfill has effectively reduced generation of leachate and resulted in an accelerated rate of water quality improvement for the area" and that "a significant decrease in the mass loading of groundwater downgradient and of the Willimantic Reservoir by the Windham Landfill has been achieved." (Beck, et al., 1982). In addition, the plume of contamination emanating from the fill appeared to recede in area and is now stabilizing. (Schuller et al., 1983).

RESOURCE REQUIREMENTS

Costs

Capital costs for caps depend primarily on the material used. At the Windham site, for example, a 20 mil PVC cap (including site preparation, 56 centimeters of sand and vegetation) cost \$4/sq. yd. A

one foot clay cap at the Vertac site (JRB, 1984, 23) cost \$2.85/cubic yd (using onsite clay) and a clay cap at the Fairchild site (JRB, 1984, 8) cost \$9.75/cubic yard (specifications of the cap not given).

Unit costs for clay caps (typical clay thickness in one to three feet) may range from \$10-20/cubic yard. These costs however may be decreased significantly by using onsite clay. Synthetic membrane caps cost between \$2-10/sq. yd. and aggregate materials (e.g. cement, concrete, asphalt) \$5-15/sq. yd. Site specific costs will depend primarily on construction related factors.

Operation and maintenance costs for surface seals are negligible. The surface seals should be inspected after storms and maintained as required to protect from erosion.

Personnel

No specific requirements.

Example

A cap may be placed over the entire source area of the example site as part of a program to contain the source of contamination. The site is first graded, followed by the placement of six inches of sand, 2 feet of compacted clay, one foot of sand and gravel, 2 feet of top soil and vegetation. Clay is available onsite and the total area of the cap is one acre. Total cost for the cap would be \$32,000, assuming all materials are available onsite. If offsite materials are used, total cost could be as high as \$150,000. A synthetic cap using 30 mil Hypalon at the same site would cost about \$50,000 again depending on the availability of fill materials for sub-base preparation and soil cover.

SUMMARY

Caps are simple and generally inexpensive means to reduce infiltration, prevent contact with contaminated materials, and control fugitive emissions at clean-up sites. They are versatile and can be designed for most sites, although they may be difficult to install at very large sites, sites with surface obstructions, sites with extremely irregular topography, or sites with inadequate subbase stability. They require continued inspection and maintenance to insure their integrity, and with proper design and cover stabilization (e.g., revegetation) they may be suitable for post-closure use (e.g., park; buildings). With the use of sophisticated designs, including impervious synthetic liners, proper drainage, and a revegetated soil surface, infiltrations of surface water can be substantially reduced, if not prevented entirely. Vents may be required to prevent gas buildup from cracking the cap.

6. Solidification and Stabilization

DESCRIPTION

Solidification and stabilization technologies reduce the potential for leachate production by binding waste in a solid matrix via physical and/or chemical process. Wastes are either mixed with a binding agent and subsequently cured to a solid form. Detailed descriptions of these technologies can be found in EPA, 1982; Ehrenfeld and Bass, 1983; and U.S. Army, 1980.

CAPABILITY

Range of Applicability

Stabilization or solidification was used at 4 of the 23 sites discussed in JRB, 1984. Wastes amenable to treatment by this technology "consist mainly of inorganic materials in aqueous solution or suspension [which] contain large amounts of heavy metals or inorganic solids. Organic wastes and waste streams containing organic constituents are less amenable to contaminant fixation by state-of-the-art processes" (Sims and Wagner, 1984).

Type of fixative used will depend primarily on the characteristics of the wastes. Organic fixatives include asphaltics and bitumens, and phenolics, epoxides, and polyesters and vinyls. Inorganic fixatives include cements and concretes, calcium compositions, silicates, and sulfate compositions. "Inorganic cements are the most commonly used fixatives and are employed mainly for fixing heavy metal contaminants, even though organic fixatives are generally more chemically stable than inorganic ones. They are also more physically stable, but as reinforced materials, their load-bearing properties may not be comparable. Raw material costs considerations and familiarity presently favor the use of inorganic fixatives". (Sims and Wagner, 1984).

The important site factors involve the logistics of mixing the waste with the fixative. The remedial action design should include a strategy for mixing the wastes. It is also important to consider post-closure site use. Bearing capacity of the stabilized material may be important if the site is to be capped and subsequently redeveloped.

Effectiveness

Solidification and stabilization technologies are designed to prevent the waste from leaching. They are often used in conjunction with a cap to prevent water from contacting the stabilized waste. Types of products formed include solid solutions (sub-microscopic contaminant particles, most likely in the molecular and colloidal size range, dissolved in a solidified fixative and characterized by weak chemical

interactions such as Van der Waals forces); chemically fixed products (sub-microscopic contaminant particles, most likely in the molecular and colloidal size range, incorporated in a fixative and characterized by strong chemical interactions with the fixative such as chemical bonds), and microencapsulations (microscopic and macroscopic contaminant particles individually encased in a fixative that does not significantly affect the contaminant molecules because they are unavailable for interaction). Most solidification and stabilization technologies currently available involve microencapsulation rather than chemical fixation. (Sins and Wagner, 1984).

The principal technical uncertainty with these technologies is the long-term viability of the stabilized material to prevent leaching of waste constituents. Short-term tests are conducted to demonstrate technology effectiveness for a given application, although long-term effectiveness can only be verified by field data. Regardless, it is clear that a higher degree of containment is achieved with stabilized or similarly treated wastes in combination with other containment measures such as a cap than with untreated wastes.

Reliability

Monitoring data to verify the effectiveness of these technologies in containing wastes is limited. For example, at the Trammel Crow site (JEB, 1984, 21), 5 million gallons of sludge oil (25,000 cubic yards) was solidified using kiln dust. Sludge was removed from a pond, solidified, and then placed in an on-site landfill which was subsequently capped. Laboratory data indicated that a 3:1 ratio of kiln dust to sludge was required for proper solidification. Under field conditions, however, only a 3:2 ratio was required, thus reducing project costs. While the kiln dust was effective in stabilizing the sludge from a mechanical properties perspective, no monitoring data are available to verify its effectiveness in preventing leaching. Long-term viability of containment at this site will depend not only on the characteristics of the stabilized sludge over time, but also on the effectiveness of the cap to exclude water from the waste material.

In general, reliability will be limited by inhomogeneities in waste composition and distribution through the contaminated region. Effective immobilization depends on achieving a high degree of mixing and the absence of constituents that would interfere with the stabilization process. Given the typical conditions that are found at clean-up operations and the difficulty of working in the field, the reliability of this type of process will be uncertain.

RESOURCE REQUIREMENTS

Costs

Costs for stabilization or solidification will depend on the technology used, the volume of the waste, pretreatment requirements including excavation of materials, and costs of additives. At the Trammell Crow site, for example, 25,000 cubic yards of sludge were solidified for about \$400,000. About \$150,000 was spent on kiln dust and \$215,000 on excavation and solidification of the material. The remaining amount was a bonus paid to the contractor for minimizing the amount of kiln dust required. Unit costs at the Trammell Crow site were \$16/cubic yard of stabilized sludge.

Unit costs for stabilization and solidification technologies vary considerably from site to site, and depend on the technology which is used. At a site in Massachusetts, for example, bids received to solidify 13,000 cubic yards of sludge range from \$60-100/cubic yard. This range is significantly higher than the \$16/cubic yards at the Trammell Crow site.

Personnel

No specific requirements.

Example

The lagoon at the example site contains about 60 cubic yards of sludge. This material is to be stabilized using kiln dust. The stabilization process involves excavating the sludge from the lagoon, mixing with kiln dust and replacing back into the lagoon. Total cost for this operation would be about \$5000-10,000.

SUMMARY

Solidification and stabilization technologies offer promise in increasing the reliability of source containment options at clean-up sites. In combination with caps and barriers, leaching would be reduced substantially relative to systems involving the caps and barriers alone. There remain questions as to the long-term integrity of the resultant matrices. Freeze-thaw cycles may cause cracking in the wastes above the frost line. Non-uniform conditions at a site and operational difficulties may result in pockets where incomplete immobilization has occurred. In many cases, inexpensive additives such as cement or flyash can be used. None of the more extensively used and tested systems work in the presence of significant quantities of organic compounds. This is a severe limitation as organic contamination is present at a majority of clean-up sites. Extensive testing is necessary to determine the proper mix of wastes and additives.

7. Encapsulation

DESCRIPTION

Encapsulation is a process in wastes are enclosed in a stable water-resistant material. The process may be applied to wastes in containers, such as drums, or to wastes that have been bound into a matrix of sufficient strength to hold together while the covering is applied. One process developed by TRW Corporation uses a $\frac{1}{8}$ inch-thick layer of high density polyethylene as the covering material (USA, EPA, 1980). The encapsulated wastes are then placed in a landfill.

CAPABILITY

Range of Applicability

Encapsulation can be applied to wastes in containers small enough to fit into the process equipment and any wastes that can be stabilized sufficiently.

Effectiveness

Leaching potential of encapsulated wastes is nil to very low as long as the covering is intact.

Reliability

No long term data are available on the long-term stability and integrity of the covering materials. The materials are capable of withstanding freeze-thaw cycles (EPA, 1982).

Resource Requirements

No information available.

8. Vitrification

DESCRIPTION

Vitrification is the melting of soil and wastes, by passage of an intense electric current through the soil. The resultant high temperature fuses the materials. After they cool back to ambient temperature, they are bound into a glassy, solid matrix. The vitrified portions of the matrix are very impermeable and prevent or substantially reduce leaching of the waste constituents. Vitrification is discussed in EPA, 1982 and Ehrenfeld and Bass, 1983.

CAPABILITY

Range of Applicability

In situ vitrification has been successfully demonstrated in laboratory and pilot scale tests on soils contaminated with radioactive wastes. The process should be compatible with non-volatile inorganic wastes/soil mixtures in general, but probably not with soils containing organic contaminants. Also, the method would be limited by the amount of water present; it is probably not applicable to saturated soil.

Effectiveness

Vitrification is a developmental technology, and therefore technical uncertainties are high. No data are available for applications to hazardous wastes. Secondary effects may include the generation of off-gases during the heating phase from volatile compounds originally present in the soil and species liberated or created at the high temperature of the process. Some volume reduction occurs and subsidence may follow.

Reliability

Data are inadequate to assess the reliability of in situ vitrification. To be effective, the resultant fused matrix must have high integrity and low permeability. It is likely that the variability of conditions at clean-up sites and presence of complex mixes of contaminants would severely lessen the reliability of this method. It would be difficult to determine the completeness of the treatment throughout the contaminated zone. Few data exist on long-term reliability (resistance to leaching).

RESOURCE REQUIREMENTS

No information available.

SUMMARY

Vitrification may have limited applications to clean-up at sites where the wastes conform to its design requirements. It is still very much a developmental technique, is expensive, and its long-term reliability for leaching prevention has not been examined in applications to hazardous waste. If found to be practical, it can treat wastes in situ and provide a more permanent containment solution than the use of barriers, for example.

D.. Treatment Technologies

As noted earlier, the potential applicability of treatment technologies depends primarily on the waste characteristics. Table 3 matches the major treatment techniques to broad classes of chemicals.

1. Biological Treatment

DESCRIPTION

Biological treatment utilizes microorganisms to degrade or remove contaminants from a waste stream. Important biological treatment processes include activated sludge, aerobic stabilization ponds (surface impoundments), rotating biological disks, trickling filters, and land treatment. Descriptive information on biological treatment can be found in EPA, 1982; Ehrenfeld and Bass, 1983, and Arthur D. Little, 1976. Schematic diagrams of typical systems are shown in Figures 9 to 12.

CAPABILITY

Range of Applicability

Biological treatment processes are applicable to a large number of organic wastes. Classes of compounds amenable to biological treatment are given above in Table 3.

Effectiveness

In conventional wastewater or municipal waste applications, performance of activated sludge treatment systems is typified by BOD removal efficiency. Units are typically designed to remove 85-95% of wastewater BOD load and are capable of treating BOD levels up to 10,000 milligrams per liter. In hazardous waste applications, however, removal efficiency of specific compounds or classes of compounds is a more important measure of performance.

Table 4 shows data for a selected set of contaminants. Performance of biological systems shows substantial variation from unit to unit with respect to individual compounds. Variations are due to the basic composition of the microorganisms present, the degree to which the mix has become acclimated to the wastes, the presence of interfering or toxic (to the organisms) contaminants, flow and concentration variations and other factors. Metal removal occurs by processes that attach the metal cations to the sludge. Some organic compounds, such as PCB's and polynuclear aromatic compounds, may become adsorbed to the sludge and exhibit some removal although not by biological activity. Microorganism mixes that will degrade such compounds are currently being studied.

TABLE 3
TREATMENT PROCESS APPLICABILITY MATRIX

[illegible]

Source: Ehrenfeld and Bass, 1983.

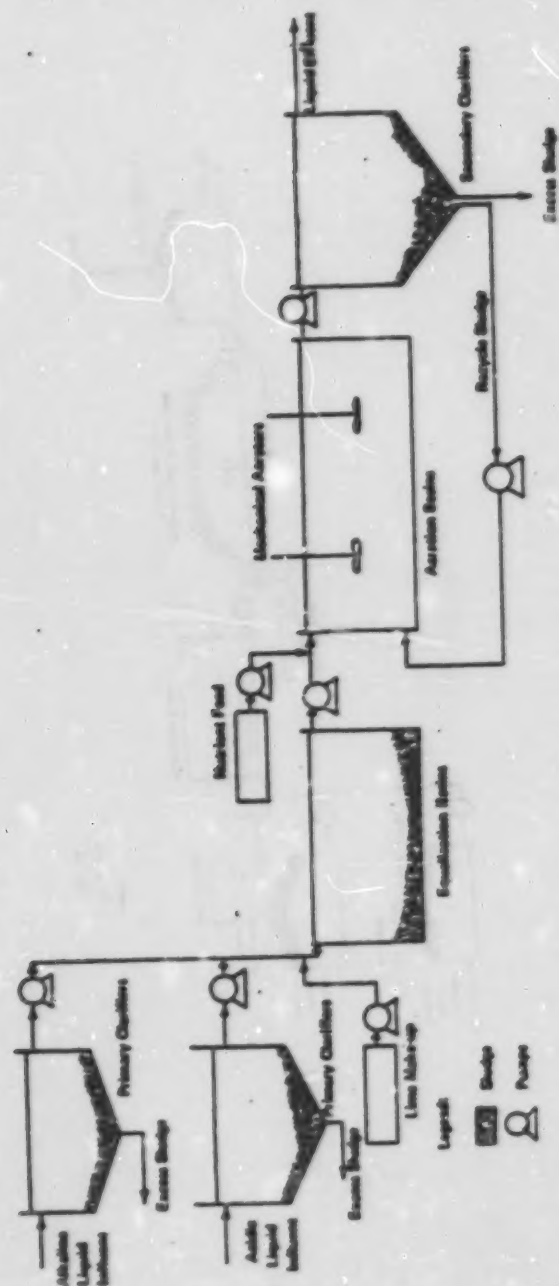
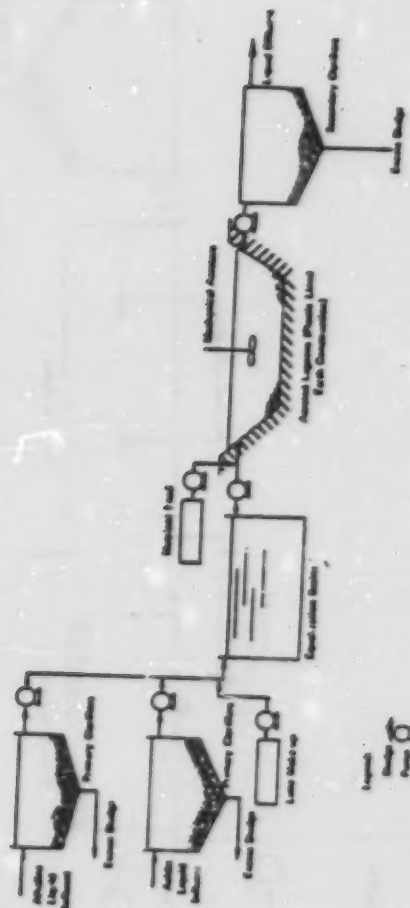


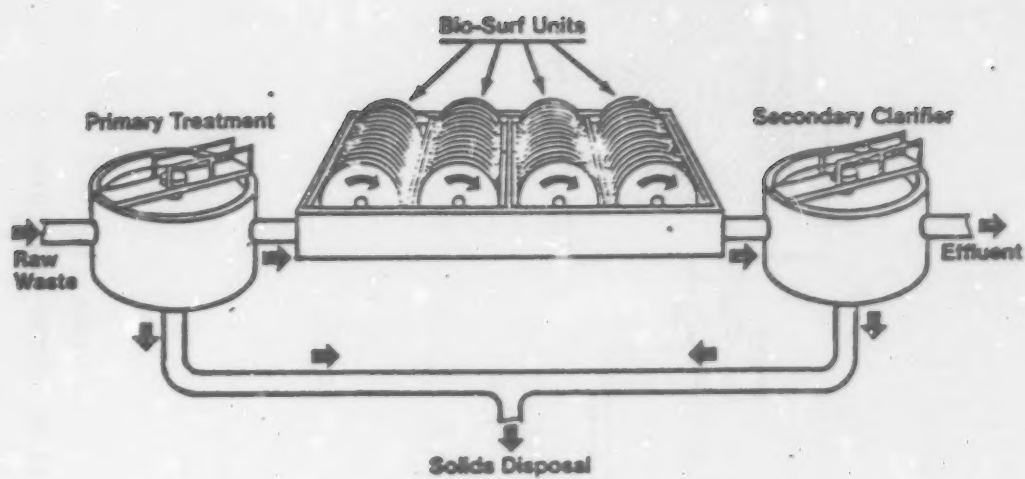
FIGURE 9
ACTIVATED SLUDGE TREATMENT FLOW DIAGRAM

Source: ADI, 1976



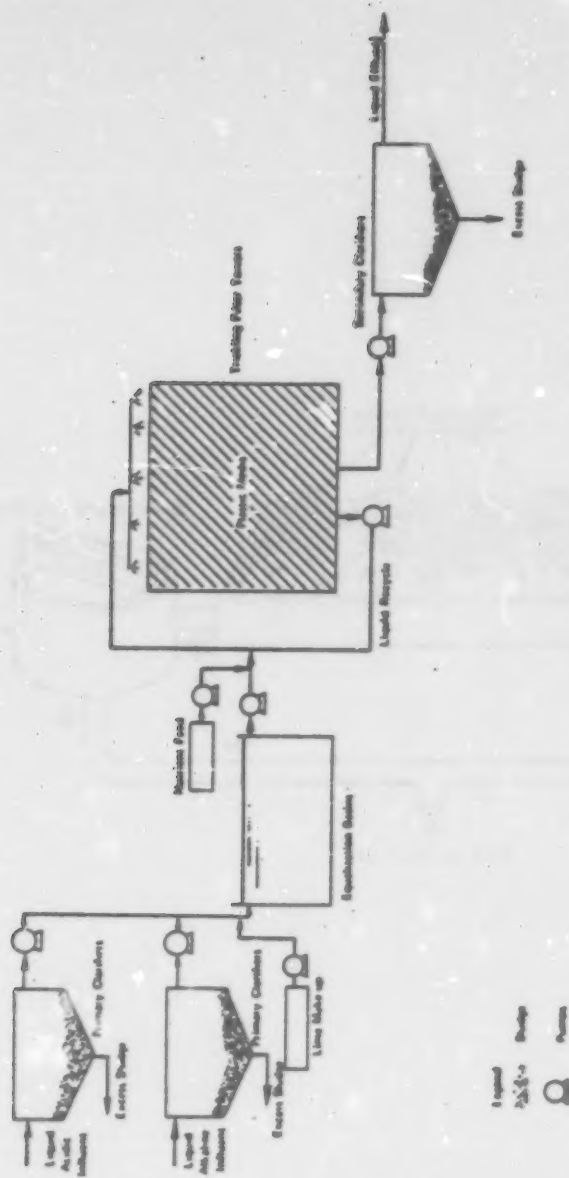
Source: ADL 1976

FIGURE 10
AERATED LAGOON TREATMENT FLOW DIAGRAM



Source: ADL 1976

FIGURE 11
ROTATING BIOLOGICAL DISC TREATMENT SCHEMATIC



Source: ADL 1976

FIGURE 12
TRICKLING FILTER FLOW DIAGRAM

TABLE 4

TREATABILITY OF SELECTED CONTAMINANTS BY ACTIVATED SLUDGE PROCESS
(Source: EPA, 1980a)

<u>Contaminant</u>	<u>Percent Removal</u>
Arsenic	43 - 96
Cadmium	31 - 99+
Chromium	45 - 99+
Copper	52 - 99+
Lead	30 - 87
Nickel	29 - 92
Phenol	82 - 99+
2-Chlorophenol	46 - 92
2,4,6-Trichlorophenol	36 - 98
Di-ethylhexylphthlate (DEHP)	37 - 99+
Benzene	49 - 99+
Chlorobenzene	71 - 99+
Hexachlorobenzene	47 - 97
Toluene	49 - 99+
Naphthalene	69 - 99
Anthracene	57 - 97
Chloroform	63 - 99
Carbon tetrachloride	0
1,1-dichloroethane	9 - 18
1,1,1-trichloroethane	74 - 99+
1,1,2-trichloroethane	>9
Trichloroethylene	63 - 99+

Aerobic stabilization ponds and aerated lagoons can normally handle waste loads equivalent to BOD levels of 200-500 mg/liter; anaerobic lagoon systems can tolerate somewhat higher levels. For wastes with BOD levels in this range and with suspended solids less than 0.1 percent, impoundments may be used as the primary method of removal. Removal efficiencies are usually in the range of 60-90%. More often, impoundments are used to polish low organic content effluent from activated sludge or trickling filters prior to discharge. Various types of impoundments have been effective in removing alcohols, amines, cyanides, phenols and phthalates. They are less effective at removing halocarbons, metals, pesticides, polynuclear aromatics, and PCBs.

Attached growth biological treatment processes, such as a trickling filter or rotating biological disc system, should be capable of treating the same type of waste as activated sludge or aerated processes. Removal efficiencies should also be comparable. Key features of rotating biological discs which may differentiate them from other systems are the characteristic modular construction, ease of operation, good settleability of solids flushed from the disc surfaces, low hydraulic head loss, and shallow excavation which makes it adaptable to new or existing treatment facilities. In addition, enclosed systems may be used to provide some protection against low temperatures.

Trickling filters reduce BOD by 10-20% when used for primary treatment (roughing) and up to 75-98% when used for high-rate secondary treatment. Trickling filters should be capable of treating the same type of waste as activated sludge or aerated surface impoundments.

Most leachates and contaminated groundwaters containing biodegradable pollutants can be at least partially treated by land treatment. Non-degradable adsorbable species including some heavy metals will be retained in the soil. The degree to which specific wastes cations will be adsorbed depends on the soil, waste loading and the competing cations. Most anions will not be retained in the soils. Removal efficiencies for BOD range from 90-99% for each of the four types of land application systems (leachate recycle, irrigation, overland flow, infiltration-percolation).

Biological treatment techniques are used extensively in wastewater applications. Technical uncertainties associated with the technologies are therefore well understood. Secondary effects of biological treatment systems are minimal, assuming that the treatment system is properly designed.

All techniques, other than land application, produce a sludge containing the remains of the organisms, unreacted organic matter and the insoluble inorganic constituents. The sludge may be considered to be hazardous, if residual toxic contaminants are present, and require additional treatment. Incineration and land disposal are the two methods used for sludge disposal.

Reliability

Removal efficiencies may decrease due to influent variability and if basic design parameters change. Biological treatment systems are very sensitive to changes in temperature, oxygen content and to toxic loadings of contaminants. For example, at the Houston Chemical Company site in Missouri (JRB, 1984, 13), insitu bioreclamation of a pond was attempted as an emergency remedial response. The pond was basically turned into an aerated surface impoundment with organisms added to increase biodegradation of PCP and oil. Expected removal of PCP was not achieved for primarily two reasons. The first is that springs at the bottom of the pond allowed contaminated groundwater to act as a continuing source of contamination. The second reason is that the property caretaker was in the habit of turning off the aeration pumps which caused many of the organisms to die when oxygen levels decreased to less than 1 milligram per liter.

RESOURCE REQUIREMENTS

Costs

Little cost data is available on onsite biological treatment at hazardous waste sites. Typical unit costs (including operating and capital recovery costs) for one million gallon per day biological treatment system are (Ehrenfeld and Bass, 1983):

- o activated sludge; \$3.63/1000 gallon (\$3.4 million capital)
- o surface impoundment; \$2.81/1000 gallon (\$2.0 million capital)
- o rotating biological discs; \$2.10/1000 gallon (\$1.2 million capital)
- o trickling filters; \$3.32/1000 gallon (\$4.1 million capital)
- o land treatment - site specific.

Personnel

No special requirements.

Example

Biological treatment of 450 gallons per minute of groundwater from the example site via activated sludge might involve a \$2-3 million capital investment and a \$500,000-\$1,000,000 per year operating cost. This assumes a removal rate of up to 10,000 ppm COD, 4,000 ppm BOD, and 6,000 ppm MLVSS.

SUMMARY

Biological treatment is a widely used (in industrial and municipal treatment), generally inexpensive method of treatment for groundwater, surface water or impounded liquids containing low concentration of organics. Although systems can be designed to achieve fairly high levels of overall removal, expressed as BOD or COD, the effectiveness for specific hazardous organic species may be quite low. For this reason, some sort of post or pre-treatment, such as carbon adsorption, may be required in addition. Treatment systems are sensitive to variations in inlet flow, composition and temperature, and to the presence of specific compounds that are toxic to the microorganisms. If upsets occur, the system may operate for sometime at lower than design removal levels. Sludges, which may be hazardous, if toxics are present, are produced. Secondary treatment of the sludges, by incineration, landfilling or land application, would be necessary.

Sensitivity to changes in inlet composition is a particular problem at clean-up sites relative to conventional treatment facilities where inlet streams are usually controlled.

2. Chemical Treatment-Neutralization, Precipitation

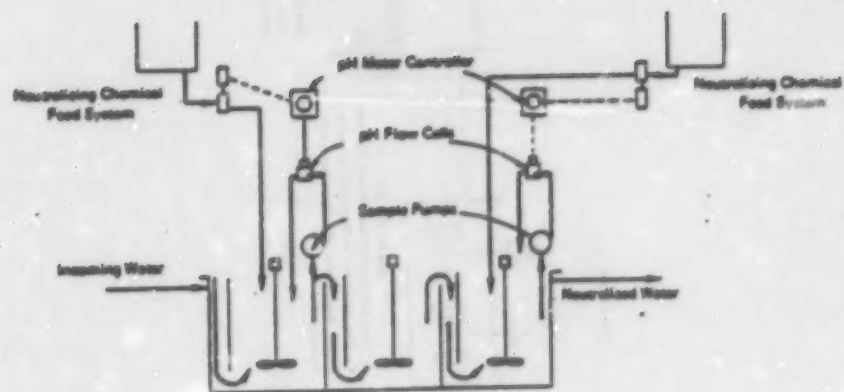
DESCRIPTION

Neutralization and precipitation are widely used processes to remove inorganic and some families of organic compounds from aqueous streams. Neutralization may be used alone or in combination with other techniques (See Figure 13). Precipitation is always used with some following steps to remove the insoluble matter that is produced (See Part 5., below and Figure 14). The processes involve the addition of chemical reagents to adjust the pH (neutralization) and/or reduce the solubility of undesired components in the waste stream (precipitation). Detailed descriptive information on neutralization and precipitation can be found in EPA, 1982; Ehrenfeld and Bass, 1983; Arthur D. Little, 1976; Adams and Eckenfelder, 1974.

CAPABILITY

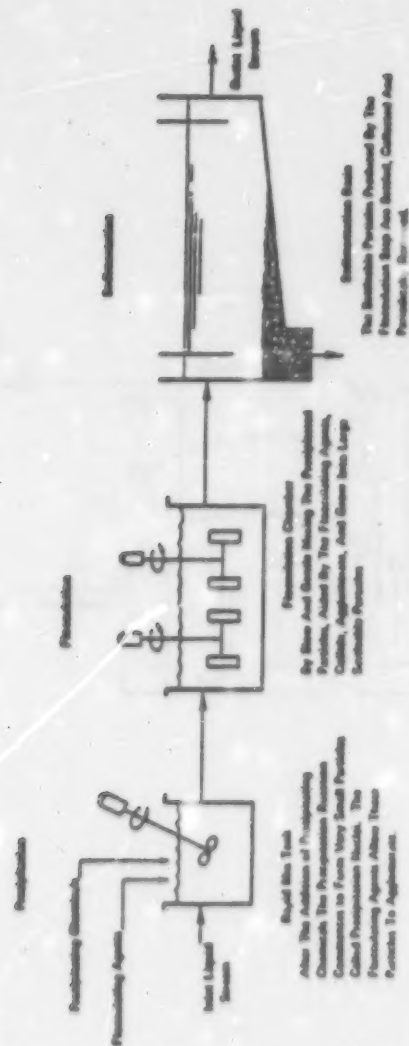
Range of Applicability

Neutralization can be used to adjust the pH of acidic or basic liquid wastes, soils or other contaminated materials. Neutralization may be used alone to reduce the corrosivity of wastes or to adjust the pH to a range where metals are immobilized. For example, at a New Jersey site, calcium carbonate (limestone) is placed on top of contaminated soil to raise the pH and maintain mercury in an insoluble form.



Source: ADL 1976

FIGURE 13
CONTINUOUS FLOW NEUTRALIZATION



Source: ADL 1976

FIGURE 14
REPRESENTATIVE CONFIGURATION EMPLOYING PRECIPITATION,
FLOCCULATION, AND SEDIMENTATION

Precipitation is used, often in combination with neutralization, to reduce the concentration of metals, and in rarer cases, organics such as phthalates to low levels in an aqueous stream. Most of the hazardous heavy metals are amenable to treatment by these techniques. Neutralization and precipitation are often used as parts of larger treatment programs.

Effectiveness

Neutralization can be accomplished with sulfuric acid, hydrochloric acid, carbon dioxide, and sodium, calcium, or magnesium-based alkalis. Each has its own strengths and weaknesses, and selection will depend on waste specific considerations. Neutralization for aqueous wastes is straightforward. Application to non-aqueous materials such as soils depends on the complexity of the site-specific situation.

The theoretical removal limits for precipitation for many metal species is very low, particularly with sulfide precipitants. For example, the equilibrium solubility of lead sulfide is in the 0.1 to 1 ppm range depending on pH. Removal in practice, however, may be one to two orders of magnitude less than the theoretical limit. Complexing agents such as cyanide or EDTA can compete with a precipitant and may hold the species in solution. Incomplete removal of precipitate may also contribute to less than theoretical performance.

Precipitation of heavy metals creates a hazardous sludge that must be managed under controlled conditions. Landfilling is the only practical alternative at present. Secondary effects associated with neutralization involve the handling of caustic and acidic materials. In addition, the effect of pH modification on soil properties should be considered in direct applications.

Reliability

The reliability of onsite neutralization and precipitation for aqueous streams is expected to be high. These processes are widely used in industrial waste water treatment. Some type of equalization (leveling of flow and concentration variations) may be necessary to maintain inlet conditions within the design range. Reliability of insitu neutralization is uncertain and neutralizing agents may need to be replaced often. No case study data were available for these technologies.

RESOURCE REQUIREMENTS

Costs

Capital costs for neutralization depend primarily on the size of the system required. Costs for a 500,000 gpd system, for example, are about 1 to 1.3 million dollars. Operation and maintenance costs for the same system are estimated to be \$1/1000 gallons treated.

Capital costs for precipitation also depend primarily on system size. Costs for a 500,000 gpd system are about \$600,000-700,000. Total cost for operating the system, including capital recovery, are about \$1.50/1000 gallons.

Personnel

No special requirements.

Example

Total costs for treating 450 gpm via neutralization and precipitation would be \$500,000-600,000 per year.

SUMMARY

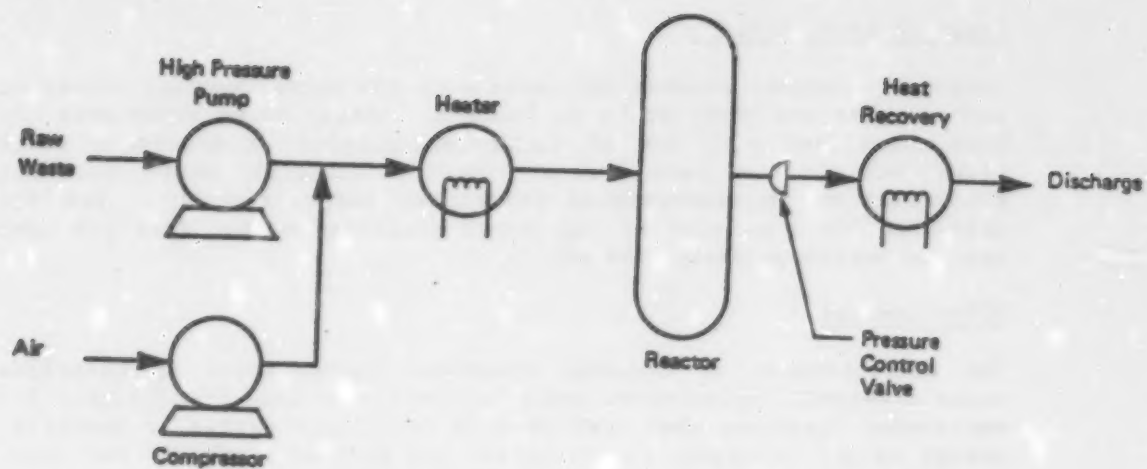
Neutralization and precipitation have very broad potential application. They are important options for treating heavy metals, and are generally quite reliable and inexpensive. They have been proven at many industrial and hazardous waste management facilities. The major problem is the creation of hazardous sludges which must be disposed of in a secure manner either on site or off site.

3. Chemical Treatment

DESCRIPTION

Various chemical treatment processes, as typified by those in the following list, can be used to treat contaminated hazardous liquids. The first two apply to specific waste types. The other two apply to broad families of organic wastes.

- o Reduction of Chromium - (See Figure 15) toxic hexavalent chromium ion (Cr VI) can be reduced to the less toxic trivalent chromium ion (Cr III) by adding a reducing agent under highly acidic conditions. The reduction process is followed by Cr III removal through precipitation as the insoluble hydroxide;
- o Alkaline chlorination for cyanide only (See Figure 16) - removes cyanide from alkaline cyanide-containing waste by oxidation in stages to the cyanate ion and then to non-toxic bicarbonates and nitrogen. Caustic and chlorine are added to the wastes in either a batch or continuous flow reactor;
- o Wet air oxidation (See Figure 17) - involves a combustion reaction occurring in the liquid phase through addition of air or oxygen at high pressure (greater than 350 psi) and elevated temperature (greater than 170°C). The products of reaction are steam, N_2 , CO_2 , and an oxidized liquid stream;



Source: Ehrenfeld and Bass, 1983

FIGURE 17
SCHEMATIC OF WET AIR OXIDATION

- o Chemical Oxidation (See Figure 18) for example, ozonation - Ozone produced in a separate generator is introduced to a contactor where it mixes with the waste and reacts with oxidizable species present. Ozonation has generally been used to treat single compounds or simple mixtures. Systems combining the action of ozone with ultraviolet light (UV) reduce ozone requirements for equivalent performance. Other chemical oxidants, such as perchloric acid, or permanganate can be used. The choice depends on the compounds(s) being treated.

Detailed descriptive information on these chemical treatment processes can be found in EPA, 1982; Ehrenfeld and Bass, 1983; Arthur D. Little, 1976; Adams and Eckenfelder, 1974.

CAPABILITY

Range of Applicability

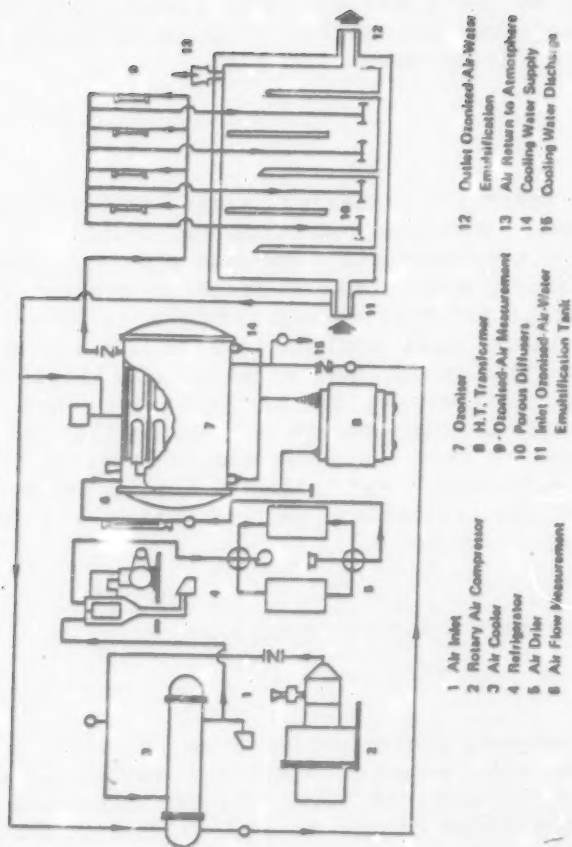
Ranges of chemical classes treatable with the above chemical treatment technologies are given above in Table 3. Little or no experience has been identified with any of these technologies at hazardous waste sites, but all have been used at regulated hazardous waste treatment facilities or in conventional industrial waste treatment. Wet air oxidation has been used to regenerate activated carbon that has been used on hazardous waste streams.

Effectiveness

The effectiveness of chemical treatment technologies in hazardous waste treatment applications would be similar to its effectiveness for wastewater treatment when used on-site for liquid wastes or leachate. Design range, technical uncertainties and secondary effects for these technologies are discussed in Ehrenfeld and Bass, 1983.

Wet air oxidation may be used as an alternative to incineration for wastes that are too dilute to burn efficiently or economically. Conversely, for wastes too concentrated (or toxic), it may substitute for biological treatment. Removal efficiencies of 40-90% are typical for non-chlorinated compounds. This technique is not very effective for chlorinated organic compounds. It is almost always used in combination with some finishing process (e.g., biological treatment, carbon adsorption) to achieve high levels of removal efficiency.

Ozonation, one of the more general of the chemical oxidation processes, can be used to treat organic compounds that are refractory to other treatment methods. Compounds that are reactive with ozone include molecules with rings and with multiple bonds.



- | | | |
|-------------------------|-----------------------------|------------------------------|
| 1 Air Inlet | 7 Ozonizer | 12 Outlet Ozonised Air Water |
| 2 Rotary Air Compressor | 8 H.T. Transformer | Emulsification |
| 3 Air Cooler | 9 Ozonised Air Measurement | Air Return to Atmosphere |
| 4 Refrigerator | 10 Porous Diffusers | Cooling Water Supply |
| 5 Air Drier | 11 Inlet Ozonised Air Water | 15 Cooling Water Discharge |
| 6 Air Flow Measurement | Emulsification Tank | |

Source: ADL 1979

FIGURE 18
OZONATION PLANT SCHEMATIC ARRANGEMENT

Reliability

No experience available to assess reliability at clean-up sites. All of these methods have been developed for waste treatment in situations where inlet conditions are relatively steady. The variable nature of contaminant streams at clean-up sites will probably limit performance relative to conventional applications.

RESOURCE REQUIREMENTS

No data is available on the costs of these technologies for use at hazardous waste sites. Cost information on these technologies can be found in the references listed above.

SUMMARY

All of these chemical treatment processes destroy the contaminants for which they are designed. Chromium reduction and cyanide chlorination are used in waste water treatment and have been widely demonstrated to be effective and reliable when used on specific concentrated waste streams. The presence of interfering constituents in mixed wastes at clean-up sites would limit their applications or effectiveness. Wet air oxidation and ozonation break down organic molecules, but not so completely as thermal destruction or incineration. New hazardous species may be produced in the process of destroying those in the wastes. It is important to test these two processes quite extensively to determine their efficiency and also the properties of their effluents. Both wet air oxidation and ozonation are expensive, requiring major capital investments.

4. Physical Treatment - Carbon Adsorption

DESCRIPTION

Carbon adsorption removes contaminants from aqueous wastes by contacting the stream with a solid activated carbon adsorbent in granular (most common) or powdered form. Organic compounds and some inorganic species become bound to the surface of the carbon particles and are subsequently removed along with the adsorbent. The adsorbent is normally regenerated, but may be disposed directly in landfills. Figure 19 shows a typical system configuration for wastewater treatment. Detailed descriptive information for carbon adsorption can be found in EPA, 1982; Ehrenfeld and Bass, 1983; Arthur D. Little, 1976; Adams and Eckenfelder, 1974.



60

CAPABILITIES

Range of Applicability

Carbon adsorption technology can achieve very high removal efficiencies for many organic compounds, particularly non-polar compounds. Many organics can be reduced to the 1-10 ppb level when carbon adsorption is used as a finishing or polishing post-treatment. Results of an EPA study showed that 51 of 60 toxic organic compounds could be removed (EPA, 1980). Some inorganics such as antimony, arsenic, bismuth, chromium, tin, silver, mercury and cobalt are partially absorbed (EPA, 1982a). Conventional water quality parameters (BOD, COD, TOC) are also reduced by carbon adsorption; the performance level is dependent on the specific waste stream characteristics.

Carbon adsorption is probably the most common treatment method for aqueous waste streams, including contaminated groundwater and leachate, for the removal of organic constituents. It is often used as part of a larger treatment system.

Effectiveness

As noted above, carbon adsorption is capable of reducing organic concentrations in the waste streams to the 1-10 ppb level depending on influent characteristics and carbon loading.

Carbon adsorption system performance is sensitive to the composition of the influent and to variations in flow. Because a system design based on expected conditions can perform poorly if influent conditions change, systems are generally oversized. Other factors which can hinder system performance are corrosion and mechanical failure, reduction in the adsorption capability of the carbon by chemicals, resins or fine precipitates in the influent, and biological activity. These difficulties, however, are well understood so that a properly designed and maintained carbon adsorption system is expected to function according to design.

The primary secondary impact of activated carbon is the need to regenerate the spent carbon. Regeneration of spent carbon may be accomplished by a variety of techniques including thermal destruction of the adsorbed organics in a multiple hearth furnace, thermal treatment with steam, extraction of adsorbed organic with solvents, and biological degradation of the adsorbed material. Carbon regenerations may be either on or off-site. Off-site regeneration has been preferred at clean-up sites. The granular carbon may then be reused, although about 5-10 percent of the carbon is lost during regeneration. Powdered activated carbon is not regenerated but is removed with the contaminants. Granular activated carbon may also be disposed of rather than regenerated based on economic or other considerations, such as the presence of highly toxic and difficult-to-destroy adsorbed species.

Reliability

The reliability of carbon adsorption is expected to be high at clean-up sites since it is a well understood and demonstrated technology and works well for many different compounds over a wide range of inlet conditions. Two examples serve to illustrate this point. At the Goose Farm site in New Jersey (JRB, 1984, 11), an extraction well pumps groundwater to a groundwater treatment system consisting principally of an aeration tank (air stripper); an activated carbon fume scrubber, a clarifier, an aqueous carbon adsorption system, and effluent storage tanks. The activated carbon fume scrubber removes volatile organics. The aeration tank removes methylene chloride which is not removed by the aqueous carbon units. The system is monitored for TOC removal and has an efficiency of about 65% with an influent concentration of 125 mg/L. Expected design efficiency, however, is not given.

At an Occidental Chemical site in New York (JRB, 1984, 17), two upflow pulsed bed contactors are used to treat effluent from extraction wells with the effluent being reinjected to the aquifer. Only one of the carbon units operates at a time with the other acting as standby. The units contain 40,000 pounds of dry carbon each and carbon is used at a rate of 5400-11,000 pounds per month. Removal efficiency of DBCP (dibromochloropropane) is greater than 99%. Average DBCP concentration in the effluent is 7 micrograms per liter with a range of ± 5 micrograms per liter. The specified performance level may be changed by the government to 1 microgram per liter. It is expected that the one microgram per liter level can be achieved with both units running in series rather than having one on standby. This system treats 300-500 gallons of groundwater per minute.

RESOURCE REQUIREMENTS

Costs

Costs for carbon adsorption may vary over a wide range depending on site specific conditions. At the Occidental Chemical site, for example, total treatment cost was \$.50-1.10/1000 gallons, while at Goose Farm, operation costs, including operating the groundwater recovery system, were \$140/1000 gallons. Typical capital costs are expected to be on the order of \$1 to 2 million, including pre- and post-treatment. Significant O&M costs include personnel to operate the system and carbon replacement.

The wide variability in costs at these two sites can be attributed to a number of factors. The level of contamination was considerably higher at the Goose Dam site, leading to a higher carbon requirement. The Goose Farm system was more complicated and included carbon adsorbers to remove the more volatile contaminants that were stripped off the wastewater prior to entering the aqueous phase adsorber units.

Personnel

Specially trained personnel are required to operate adsorption systems, particularly during startup.

Example

At the example site, treating 450 gallons per minute carbon adsorption costs might be about \$5 million/year (assume 24 hr./day, 330 days/yr, \$350,000 capital/year).

SUMMARY

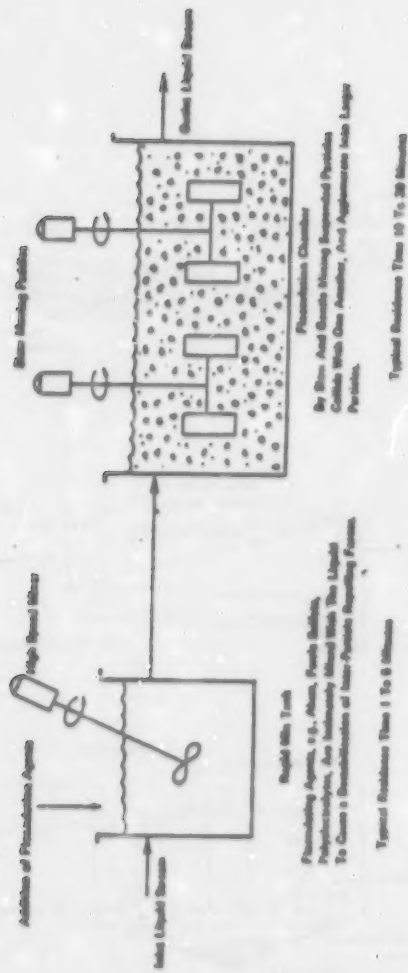
Carbon adsorption is a highly effective, well demonstrated technique for removing organic compounds, and to a lesser degree metals, from aqueous waste streams. It can treat many organic species that do not respond well to biological treatment. Systems can be designed for a wide range of inlet flow and composition conditions and of design removal efficiencies. These systems can treat streams with high organic concentrations but the cost may become excessive due to high carbon use and other O&M costs. In such cases, combinations of carbon adsorption as a finishing step with a cheaper process such as biological treatment may be more cost effective. Pretreatment stages may be needed to remove suspended solids and oil and grease, all of which would rapidly plug and deactivate the bed. Operating costs are generally high and, as noted, depend strongly on the inlet contaminant concentration. Treatment and disposal of spent adsorbent poses a secondary problem. Regeneration may require fume incineration (afterburner) to prevent transfer of the hazardous compounds from groundwater to the air.

5. Physical Treatment - General Methods

DESCRIPTION

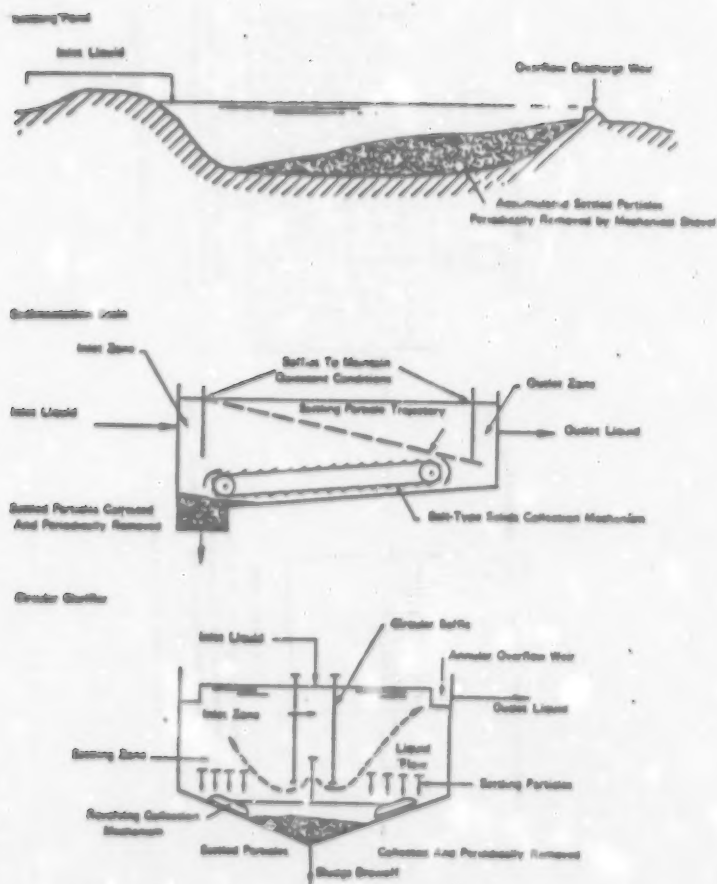
Physical treatment technologies include carbon adsorption (discussed in a separate section), flocculation, sedimentation, filtration, flotation, stripping, ion exchange, and reverse osmosis.

Flocculation, sedimentation, and filtration, (Figures 20 to 23) are used to remove suspended solids from the waste stream. Flocculation is a process in which small particles are, by adding certain reagents, brought together in larger aggregates, which are easier to remove than the original particles. Sedimentation removes suspended solids by permitting the particles to settle to the bottom of a vessel through the action of gravity. Filtration separates the solids from the liquids by forcing the fluid through a porous medium. Filtration can also be used to dewater sludges.



Source: ADL 1976

FIGURE 20
ILLUSTRATIVE FLOCCULATION PROCESS



Source: ADL 1975

FIGURE 21
REPRESENTATIVE TYPES OF SEDIMENTATION

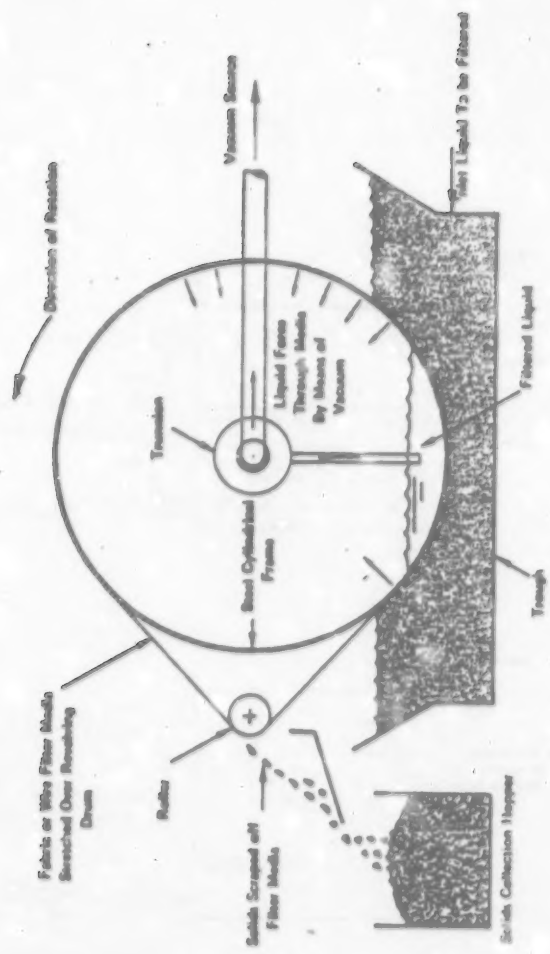
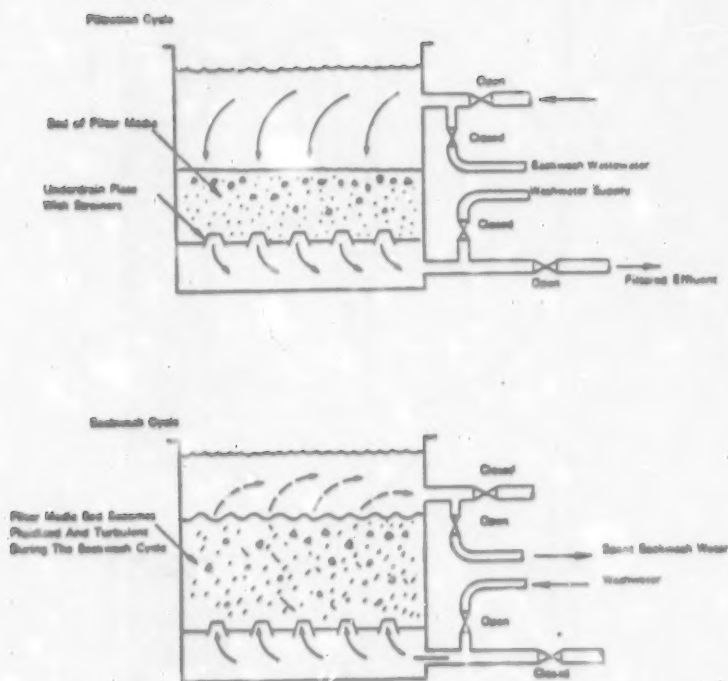


FIGURE 22
 ROTARY DRUM VACUUM FILTER
 (Cross-Sectional Side View)

Source: ADL 1976



Source: ADL 1976

FIGURE 23
GRANULAR MEDIA FILTER
(Cross-Sectional View)

Stripping removes volatile contaminants from an aqueous waste stream by passing air or steam through the wastes (Figures 24 and 25). With air, the volatile dissolved gases are transferred to the air streams for treatments such as carbon adsorption or thermal oxidation. Without effective air emission controls, this technique may exchange a water contamination problem for an air pollution problem. In some cases, direct venting of the stream to the atmosphere may be feasible, depending on the constituents and the amounts present. With steam, the process is in essence a steam distillation of the waste with the volatile contaminants ending up in the distillate for treatment.

Dissolved air flotation removes insoluble hazardous components present as suspended fine particles or globules of oils and greases from an aqueous phase. Aqueous waste mixtures are first saturated with air at high pressures and then moved into tanks under atmospheric pressure. The reduction of pressure causes small bubbles of air to form and rise to the surface. The rising bubbles carry the fine particles and small globules of oil or grease to the surface where they are skimmed off.

Ion exchange is a reversible interchange of ions between an insoluble salt or resin in contact with wastes containing ionic species. In the process unwanted ionic species, principally inorganic, are replaced (exchanged) with innocuous ions on the resin.

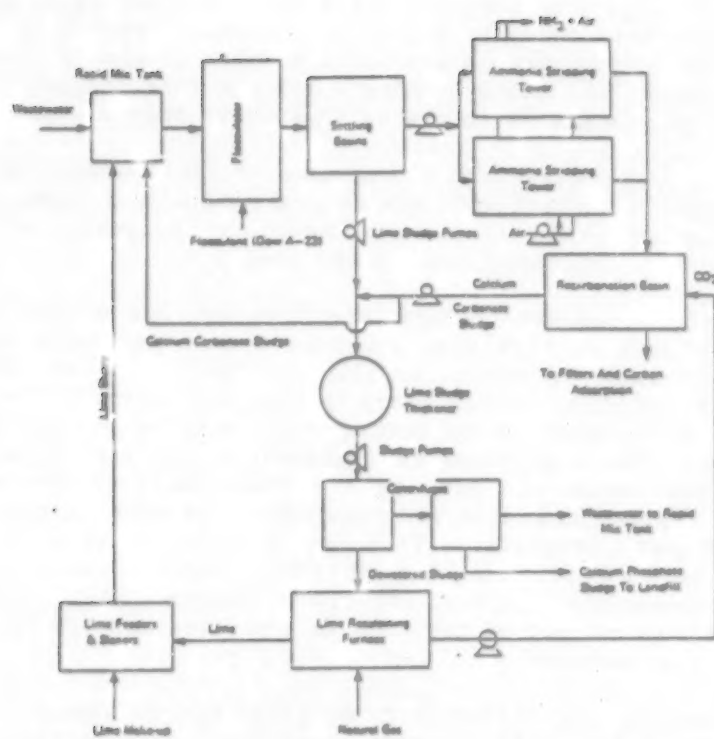
Reverse osmosis removes contaminants from aqueous wastes by passing the waste stream at high pressure past a semi-permeable membrane at sufficiently high pressure, usually in the range of 200-400 psi (Figures 26 and 27). Clean water passes out through the membrane, leaving a concentrated waste stream which must be treated further or disposed of. The high pressure counteracts the osmotic pressure of the dissolved wastes and acts as a driving force to concentrate the solution. Typical membranes are impermeable to most inorganic species and some organic compounds. They are also impermeable to very fine particles and larger molecules and will remove these as well as dissolved materials (ultrafiltration, Figure 28). Conventional particulate removal may be required as a pretreatment to minimize that fouling of the membrane.

Detailed descriptive information on physical treatment technologies can be found in EPA, 1982; Ehrenfeld and Bass, 1983; Arthur D. Little, 1976; Adams and Eckenfelder, 1974.

CAPABILITY

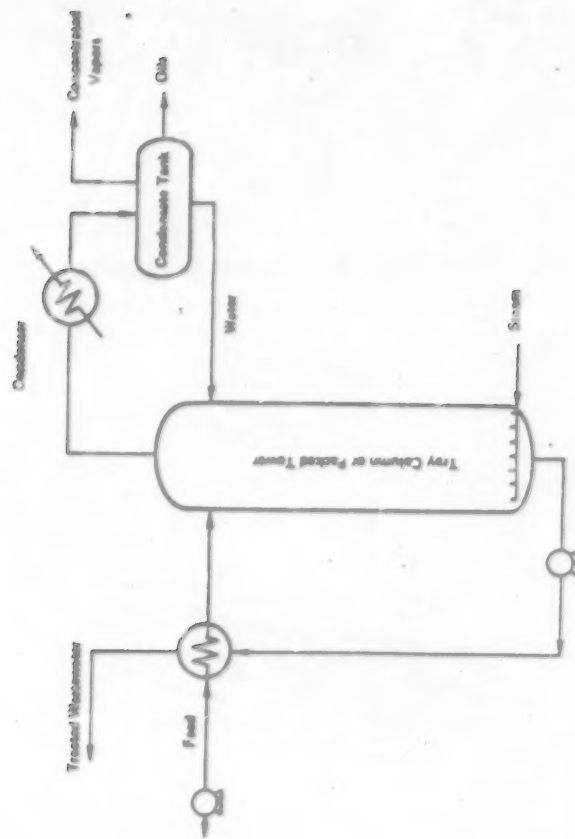
Range of Applicability

In conventional industrial waste applications, sedimentation can achieve a removal efficiency of 90-99% for wastes with reasonable settleability characteristics. There is no limitation on influent concentrations in this method.



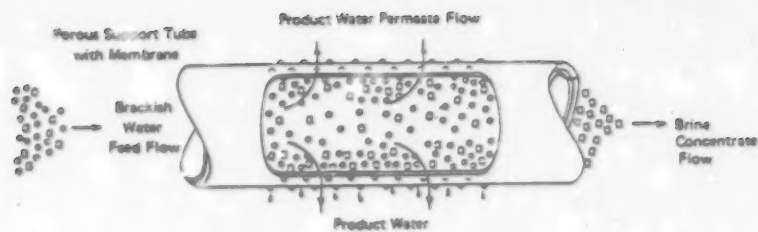
Source: ADL 1976

FIGURE 24
AIR STRIPPING OF AMMONIA FROM BIOLOGICALLY
TREATED DOMESTIC WASTEWATER

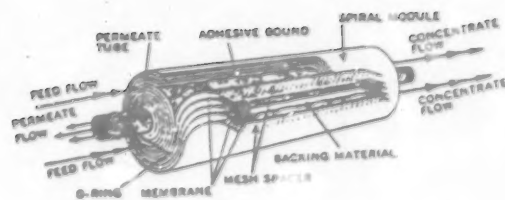


Source: ADL 1976

FIGURE 25
TYPICAL STEAM STRIPPING SYSTEM



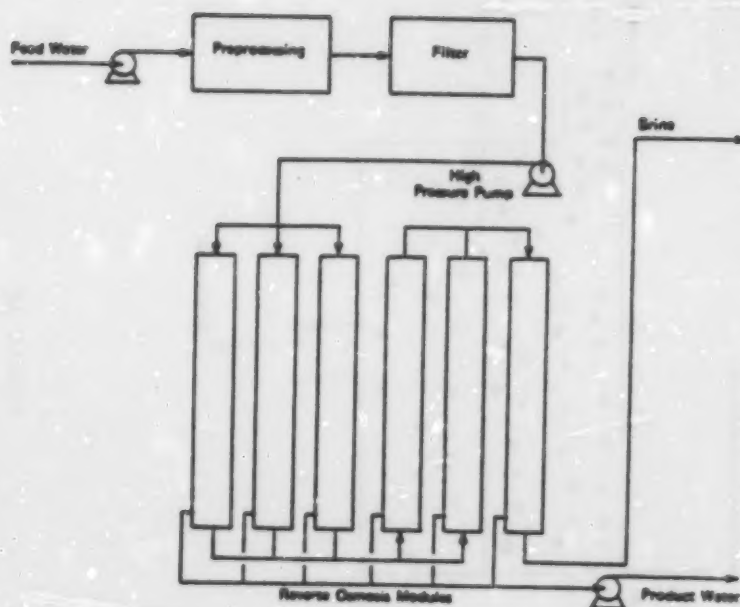
(a) Tubular Reverse Osmosis Module



(b) Spiral Membrane Module

Source: ADL 1976

FIGURE 26
REVERSE OSMOSIS MODULE TYPES



Source: ADL 1976

FIGURE 27
REVERSE OSMOSIS PLANT FLOWSHEET

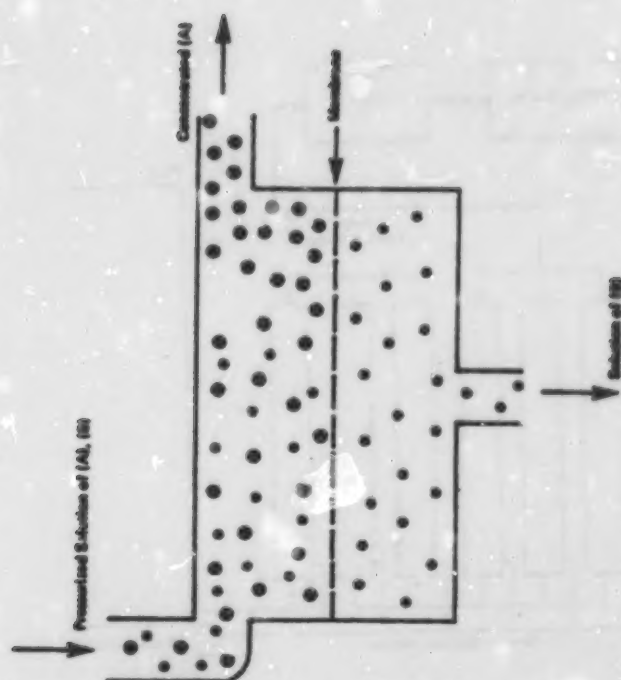


FIGURE 28
SCHEMATIC DIAGRAM OF MEMBRANE ULTRAFILTRATION PROCESS

Filtration is applicable to any liquid with filterable solids. It is also applicable to aqueous liquids containing droplets of another immiscible liquid phase such as oil contaminated water. Filtration is often used on sludges or liquids generated in the treatment of other waste streams.

Flotation can be used on suspended wastes of density close to that of water. The addition of surface active chemicals and pH adjustment are often used to enhance the sweeping action of the bubbles in the skimming operation. In industrial practice, with waste containing TSS and oil or grease levels up to 900 mg/liter, removal efficiencies of around 90% have been recorded.

Air stripping is applicable to a wide variety of volatile compounds. Removal of ammonia from wastewaters has exceeded 90% for influent ammonia concentrations of less than 100 ppm and greater than 99% has been achieved for removal of TCE from groundwater. Steam stripping can be applied to volatile organic compounds, water immiscible compounds, ammonia, and hydrogen sulfide. Removal efficiencies of volatile organic compounds from wastewater of 10% to 99% have been reported.

Ion exchange is applicable to most inorganic dissolved solids and some organic dissolved solids. Removal efficiencies for metallic ions are generally very high; data for a typical metal-containing plating waste indicate removal efficiencies of 97% to greater than 99% for all contaminants. Other chemical classes which can be treated by ion exchange include inorganic anions, organic gases, amines and various anionic and cationic species. Pretreatment to remove suspended solids may be needed.

Reverse osmosis is capable of removing greater than 99% of TDS from wastewater streams containing up to 50,000 mg/L TDS. Organics with molecular weight in excess of 300-500, such as pesticides, can be removed at efficiencies exceeding 90%. Operation is sensitive to wastewater pH, TSS levels and TDS levels. Suspended solids may have to be removed in a pretreatment step. Membrane performance may be deleteriously affected by certain organic and inorganic species. Application to mixed wastes of uncertain and highly variable composition will, as a result, be limited.

Effectiveness

Design ranges for physical treatment technologies are noted above, and additional information can be found in the literature. Technical uncertainties at hazardous waste sites arise due to the variability of influent characteristics and decreased lack of control over the treatment system. Well designed and operated units should be able to maintain treatment efficiencies similar to wastewater treatment applications.

Since the toxic constituents in the original waste streams are not destroyed in the process, the overall effectiveness must be based not only on the results of the treatment, but also must consider subsequent treatment and ultimate disposal steps. Often these processes are used primarily to concentrate the wastes for subsequent handling and to produce a treated aqueous stream that can be safely discharged to the environment (sewered or direct discharge to surface or groundwater).

Reliability

As noted above, reliability of physical treatment systems in hazardous waste site applications will generally be less than the reliability of conventional wastewater treatment systems due to increased technical uncertainties. An example of physical treatment used in hazardous waste site applications is the Quanta Resources site in Queens, NY (JRB, 1984, 19). At the Quanta site, waste was pretreated prior to discharge in the New York City sewer system. Onsite pretreatment reduced disposal costs by avoiding high-priced disposal or offsite pretreatment. The treatment system is described as follows (JRB, 1984, 26): "Oily water from tanks, separators and containment dikes was pumped into Pool I to allow the free oil to separate from the wastewater. The wastewater from Pool I was pumped into Pool II where it was acidified to about pH 4 to break any oil emulsion to allow the oil to separate from the water. Wastewater from either Pool I or II was pumped to chemical mix tank I and treated with caustic to raise the pH 11 to 12. A polymer was also added to aid the agglomeration of flocculant formed in alkaline solution. After pumping this alkaline wastewater to chemical mix tank II from chemical mix tank I it is acidified to pH 6-9 to be compatible with the storage in pools III, IV and V and the sewer system. A clarifier tank was then used to allow the solids, heavy metals and PCB to precipitate and settle. Finally, a sand filter filled with uniformly graded sand was used to filter out any flocculant solids or any other particulate matter that did not settle out in the clarifier." Treatment efficiencies attained by this system are not given in the reference.

RESOURCE REQUIREMENTS

Costs

Cost information for sedimentation, filtration, flotation, stripping, ion exchange and reverse osmosis can be found in EPA, 1982. Unit costs for steam stripping, ion exchange and reverse osmosis are high compared to other treatment technologies. Examples in EPA, 1982 give the unit costs for these technologies at \$21/1000 gallons, \$9/1000 gallons and \$3.45/1000 gallons respectively. Unit costs for filtration using vacuum filtration range from \$40 to over \$100 per ton of dry solid processed.

Personnel

Highly trained personnel are needed to operate the physical technologies.

Example

Total cost to treat 450 gpm of contaminated groundwater using sedimentation and reverse osmosis would be on the order of \$2.5 million per year.

SUMMARY

Physical treatment systems are widely used in conventional wastewater treatment. Methods are available to treat many types of wastes over a wide range of inlet conditions. Nevertheless, the combinations of wastes found at clean-up sites may limit the application or achievement of high levels of removal. None of the methods discussed in this section destroy the contaminants. Some additional means of disposal or treatment will be required. Some of the systems removing inorganics will produce a sludge or solid that must be sent to a secure landfill for disposal. Reverse osmosis and ion exchange produce a dilute aqueous stream containing the species that have been removed. Stripping transfers the volatile compounds to a gas stream where they may be destroyed by thermal oxidation or treated by other techniques. These systems range in cost from quite low (sedimentation, filtration) to quite high (ion exchange, reverse osmosis). Most of these are used in combination with other treatment processes.

6. Gaseous Streams - Thermal Oxidation

DESCRIPTION

Thermal oxidation destroys hazardous components in a gas by combustion. The two principal types of thermal oxidation systems are:

- o flaring - a flare consists of an ignition chamber in which an ignitable gas is allowed to combust in a controlled air environment. A pilot burner is used to ignite the vent gases. In smokeless flares steam is added to convert any unburned heavy hydrocarbons to carbon dioxide and hydrogen. Flares may be used to burn up methane containing gases produced by anaerobic decomposition in landfills containing municipal or mixed wastes.
- o afterburners - where the off-gases are not inherently ignitable or do not contain sufficient heating value to achieve the desired decomposition temperature, additional fuel is added to the waste gas stream to generate the requisite high temperature after combustion. Incoming gas and vapors plus fuel (if necessary)

combustion. Incoming gas and vapors plus fuel (if necessary) pass through the afterburner where they decompose at the high temperatures in the presence of oxygen. The products are carbon dioxide, water, and other combustion products. In some cases, afterburners incorporate a catalyst to facilitate oxidation at lower temperatures, without auxiliary fuel addition.

Afterburners and flares are used in conjunction with pipe vents, which channel the flow of gases to the inlet of the thermal oxidation system. Detailed descriptive information on thermal oxidation for gaseous streams can be found in EPA, 1982; and Ehrenfeld and Bass, 1983.

CAPABILITIES

Range of Applicability

For flaring, the gases to be treated must be inflammable, with heating values greater than 100 Btu per cubic foot. Only gases containing fairly large amounts (10% or more) of biogenically produced methane will meet these requirements. Thus, application of flares would be limited to sites where mixed wastes are present and anaerobic decay produces sufficient methane. Off-gases from strippers may, in some cases, be sufficiently combustible to permit use of flares. Halogenated compounds are not combustible, per se, and should not be treated in a flare.

Afterburners, on the other hand, can be used to treat gas streams with a much wider range and concentration of organic contaminants. The amount of auxiliary fuel required depends on the heating value of the incoming stream and on the desired combustion temperature. This type of system can be used to destroy contaminants vented directly from the clean-up site or contaminants in the off-gases from another treatment process, such as air stripping.

Effectiveness

The effectiveness, measured in destruction efficiency, of afterburners depends on the temperature of combustion, residence time, and the inherent destructability of the contaminants. Very high efficiencies, in excess of 99.9%, are obtainable by operating at temperatures in excess of 1200°C, with residence times in excess of 2 seconds. These conditions match those required or implied by stringent RCRA incineration standards. Conventional industrial afterburners often are designed to less demanding standards.

Flares cannot achieve such high destruction efficiencies.

Reliability

Thermal destruction of fumes from a packed tower air stripping unit is being employed at the Sylvester, N.H. site. No data, however, are available on the system's effectiveness.

RESOURCE REQUIREMENTS

Costs

Installed costs for a flare system range from \$2250 to \$4500 for 20 to 670 cubic feet per minute gas flow. Operating costs for flare systems are negligible.

Installed costs for afterburning vary widely and are presently estimated to be on the order of \$25/standard cubic foot per minute. Annual operating costs have been estimated to range from \$10-50/cubic foot per minute.

Personnel

No special requirements.

SUMMARY

Thermal oxidation, using afterburners, is a proven method for cleaning up gas streams emanating from the waste site or from water treatment processes (carbon regeneration, stripping). Very high removal efficiencies can be obtained for almost all organic compounds, including chlorinated hydrocarbons. Auxiliary fuel requirements and, as a result, operating costs increase with increasing efficiency. Flares are not applicable to clean-up operations.

7. Gaseous Streams - Carbon Adsorption

DESCRIPTION

Carbon adsorption systems for air emissions consist of a tank, drum, or other container that supports a bed of activated carbon. Contaminated gas flowing through the carbon bed is adsorbed on the carbon surface due to Van der Waals attraction and chemical bonding. The adsorbed gases can then be removed from the carbon by raising the temperature, often by the use of steam. The regenerated carbon can be reused. Detailed descriptive information on carbon adsorption for air emissions can be found in EPA, 1982; and Ehrenfeld and Bass, 1983.

CAPABILITIES

Range of Applicability

Carbon adsorption is a widely used technique for removing organic contaminants from gas streams. It can be applied at clean-up sites to vent gases from other treatment processes, such as stripping, or directly to gases seeping out of the waste mass. Most organic

compounds of molecular weight exceeding about 50 are amenable to treatment with this technique. It can treat complex mixtures as easily as simple gas streams.

The carbon is generally regenerated and reused for many cycles. Some high molecular weight compounds are difficult to desorb and may limit or preclude the use of regenerative configurations.

Effectiveness

Removal efficiencies for carbon adsorption of gas streams can be very high. Residual concentrations can be reduced to the sub-ppm level. High molecular weight compounds are more strongly bound than lower weight, and thus, are more efficiently removed. Non-polar compounds are absorbed more strongly than polar ones. Secondary impacts include the need to replace or regenerate spent carbon and to dispose of any desorbed constituents produced during regeneration.

Reliability

No data are available describing experience with carbon adsorption for gas streams at hazardous waste sites. The technique has been widely used in industrial applications and should function reliably in clean-up settings. Adsorption equipment is quite insensitive to changes in inlet concentrations.

RESOURCE REQUIREMENTS

Costs

Total installed costs for a non-regenerative carbon adsorption system treating vent gas containing 50 ppm of trichloroethylene ranges from \$40,000-110,000 for a flow rate ranging from 1,000-10,000 cubic feet per minute. Annual operating costs for the same flow rate ranges from \$160,000-1.5 million per year (Khrenfeld and Bass, 1983).

Personnel

No special requirements.

SUMMARY

Carbon adsorption is a widely used, well-understood technique for removal of organic components from gas streams. It can be very effective (>99.9% removal) for most organics, but has lower performance for lower molecular weight, polar species. The method is quite expensive, requiring high capital costs and high operating costs (carbon consumption and disposal). The organic contaminants are not destroyed (in non-regenerative systems) as in thermal oxidation so some other means of treatment or disposal is required. Afterburners

may be used in combination with regenerative systems where the combinations are cheaper to operate than an afterburner alone. The combination can reduce fuel costs substantially. Alternatively, the non-regenerative mode can be used, but at the expense and risk of disposing the materials in a landfill or incinerator.

8. Liquids/Solids/Sludges - Incineration

DESCRIPTION

Incineration combusts or oxidizes organic material at very high temperatures. The end products of complete incineration are CO_2 , H_2O , SO_2 , NO_x , and HCl gases. Emission control equipment (scrubbers, electrostatic precipitators) for particulates, SO_2 , NO_x , and products of incomplete oxidation are needed to control emissions of regulated air pollutants. Common types of incinerators most applicable to hazardous wastes include rotary kilns, multiple hearth, fluidized bed, and liquid injection. Detailed descriptive information for incineration can be found in EPA, 1982; Ehrenfeld and Bass, 1983; Arthur D. Little, 1976.

CAPABILITY

Range of Applicability

Wastes may be removed to an off-site incinerator for disposal or fed into a unit located onsite. On-site units may be semi-permanent (constructed from the ground up) or may be mobile units brought to the site as component units and assembled on-site.

Incineration is effective for essentially all organic contaminants, particularly if they are present as liquids. Sludges and contaminated soils require special incinerators, usually rotary kiln types (similar to cement or lime kilns).

Although there are commercial available techniques for on site incineration, the technology has not been used at actual cleanup sites. Institutional reasons appear to be a major factor (most state agencies consider that a mobile incinerator must be sited as a RCRA facility). The U.S. EPA, however, is continuing the process of developing a mobile incineration unit for application at hazardous waste sites. The system is being developed by IT Corporation for the Oil and Hazardous Materials Spills branch of the EPA. This system consists of a rotary kiln incinerator, a secondary combustion chamber and quench, and air pollution control with an induced air draft blower, each of which is transported on a semi-trailer. The unit has been developed for research purposes and to stimulate commercial interest in mobile incineration. It is therefore not specialized but can handle solid, liquid and sludge materials, including drummed waste, bulk liquids, and soils that are contaminated with refractory,

toxic organics to levels of several hundred mg/kg. The primary site factor for a mobile unit would be sufficient space to set up the three trailers, feedstock preparation areas, analysis areas, etc.

On-site incinerator operations require substantial supporting activities. Permitting requires the development of engineering data and may require expensive test burns. Facilities for treating and disposing of scrubber sludge and liquid effluent must be installed. Substantial electric power is required.

Effectiveness

Information on the test burn of the mobile incineration unit is not currently unavailable. Performance should (must) match that of permitted units; >99.99% destruction and removal for hazardous wastes as defined by RCRA and >99.9999% for PCBs (TSCA). Design requirements for the unit include highway weight and size limitations, the EPA specifications for incineration of PCB's, and air pollution control requirements for particulates, carbon monoxide, sulfur dioxide, and hydrogen chloride.

Secondary effects of incineration include residue disposal, possible exposure to unburned contaminants or toxic products of combustion in the stack gases, scrubber sludge disposal, and scrubber effluent discharge. Removing the wastes to an off-site incinerator would shift the locus of the secondary effects relative to the population in the vicinity of the clean-up site. Large quantities of residues would result from incinerating contaminated soil. It is likely that these materials would have to be placed in a RCRA-permitted secure landfill as many states treat incinerator residues from hazardous wastes as hazardous.

Reliability

Off-site facilities would be proven and permitted, and would be expected to be highly reliable. The effectiveness of on-site incineration as a treatment method for destroying hazardous waste is expected to be very reliable. On-site systems should be able to achieve the same types of destructive efficiencies as off-site systems. On the other hand, neither mobile or specially constructed units would have all of the features of a permanent, commercial unit.

RESOURCE REQUIREMENTS

Costs

Costs for onsite incineration are difficult to estimate since there is no actual site experience. A preliminary estimate for fuel-oil fired field use of the EPA Mobile Incineration is about \$10,000/day. At a feed rate of 3000 lb/hr, this gives a unit cost of \$.28/lb or \$555/ton based on a 12-hour day. Costs at commercial facilities run from about \$100-200 tons for combustible liquids to as much as \$800-1000/ton for PCB liquids.

Costs for on-site incineration would include (in addition to the basic equipment costs) permitting costs, water supply (for quenching and scrubbing), sludge and all handling and disposal, scrubber effluent treatment and disposal, and decommissioning of the facility.

Personnel

Specially trained personnel are required. Incinerators require a fairly large complement of field personnel.

SUMMARY

Incineration, although not widely applied to clean-up operations as yet, is capable of nearly complete destruction of all organic compounds present. Limited quantities of wastes and contaminated soils can often be (and have been) safely transported to off-site incinerators. This mode may be impractical (expensive and risky) at clean-up sites where large quantities of contaminated materials must be treated. In these cases, mobile units or field-erected systems can be installed on site. No demonstration of such a concept has yet been implemented. For economic and engineering reasons, field-erected or mobile incinerators are considerably smaller in daily capacity than are some of the larger currently operating commercial units. As a result, on-site treatment could take longer to complete than the off-site alternative.

The residue from incineration may be considered to be hazardous and, if so, would require disposal in secure facilities, but the risks involved would be very much less than if the wastes were disposed of directly. New technologies involving high temperature processes are under development. These may be able to reduce levels of difficult-to-treat wastes such as 2, 3, 7, 8 TCDD (dioxin) or PCB's on soil to vanishingly small concentrations. Incineration is generally quite expensive. Treating contaminated soils would be considerably more expensive than treating conventional hazardous wastes because of the very high ratio of inerts to wastes and the low (virtually zero) heating value.

Extensive and expensive pilot testing and on-site test burns would be required. Public opposition to incineration and permitting requirements, if applicable, could create substantial obstacles to the use of this technology.

9. In Situ - Biodegradation

DESCRIPTION

Biodegradation involves the use of naturally occurring or synthetically generated bacteria to break down chemicals via ingestion and respiration. Bacteria may be developed to break down specific

constituents in soil and can be purchased in bulk quantity for that purpose. These materials were originally developed for treating spills and leaking tanks. Most biodegradation processes used to treat hazardous wastes are aerobic; the technique usually used is to seed the waste material in situ with microorganisms, or to transport and spread the waste over aerated soils (land treatment). Surface impoundments or ponds in which the wastes may be mechanically aerated are also candidates for using in situ biodegradation. More recently, several concepts have been developed in which the biodegradation occurs within the saturated, contaminated soil/groundwater system. In this configuration, nutrients and oxygen are injected directly into the groundwater. Oxygen is added by pumping air into the ground through well points located below the water table. Some systems rely on the indigenous microorganisms; others inject additional microorganisms together with the nutrients. All pump and recirculate groundwater, since it takes more than one pass to obtain high removal efficiencies. Biological treatment, discussed separately, is based on the same fundamental processes. Detailed descriptive information of in situ biodegradation can be found in Ehrenfeld and Bass, 1983.

CAPABILITY

Range of Applicability

In-situ biodegradation is most applicable to surface contamination and spills where oxygen is readily available. Aeration wells, however, can be used to provide oxygen at depths greater than two feet.

Biodegradation has most commonly been employed for treatment of oil residues. In addition, oil contaminated beaches and a formaldehyde spill in California have been cleaned up using commercially available microbes. Mutated organisms have been shown to break down pesticides and organic solvents. "Use of thermophillic organisms in composting process has shown degradation of complex compounds such as chlorophenols and chlorobenzenes; insecticides, diazonium, parathion and dieldrin; chlordane; grease and oils; crude oil; TNT and pulp and paper mill wastes; and pharmaceutical wastes". (Srivastava and Haji-Djafari, 1983). Bacteria developed for biological seeding are also capable of degrading benzenes, phenols, cresols, naphthalenes, gasolines, kerosenes, and cyanides.

Effectiveness

Extent of microbial degradation depends primarily on hydraulic loading, oxygen content, organic carbon content, C:N:P ratio, buffer strength, supplemental energy (carbon) source, and pH. For subsurface treatment of groundwater, residence time of the groundwater in the aerated and seeded area is important. Performance of in situ biodegradation will depend on how well these factors can be maintained at optimal conditions and on the suitability of the microbes to degrade the wastes. Overall effectiveness at an actual field site

will be limited by the difficulty of maintaining the proper mix of organisms, nutrients, oxygen, and contaminant level throughout the entire, generally inhomogeneous contaminated zone. Further, some organics may be toxic to the organisms. On the other hand, if growth is robust, microorganisms may plug the soil and interfere with further degradation down-gradient. Complete or near complete removal, under most field conditions, would be difficult to achieve or would require long treatment times.

Secondary effects of in situ biodegradation are low. They include disposal of spent microbes, the generation of gases, and low concentrations of undegraded products. There are no apparent health hazards associated with current biodegradation techniques.

Fugitive emissions due to the disturbance of surface layers, when microorganisms are mixed in, would have to be controlled. Some species (dioxin, PCB's, polynuclear aromatics) are quite persistent and are difficult to degrade in the soil matrix or in sludges. Extensive monitoring would be required to determine the effectiveness of this technique for all the individual contaminant species present.

Reliability

The performance of in situ biodegradation in the field is difficult to assess due to lack of information. At the Biocraft Lab site (JRB, 1984, 4), nine aeration wells were placed in the plume to enhance microbial activity. In addition, a bioreactor was used to treat groundwater extracted down-gradient of the aeration zone. Reported removal efficiencies were: methyl alcohol - >98%, methylene chloride - >98%, acetone - >89%, n-butylalcohol - >97%, and dimethylaniline - >64% (>93% for the last six months of period monitored). The wells were thirty feet apart and had a calculated radius of influence of 15 feet with an air injection rate of 4-9 psi. The residence time was calculated at 65 - 300 days, depending on the direction of groundwater flow through the aerated zone. Aeration occurred at a depth of about 10 feet. No test data is available to verify the effectiveness of performance of the aeration system. There is also some uncertainty about the expected effectiveness of the system, since the 15-foot radius of influence was not tested. If the radius of influence of the wells is less than 15 feet, then the zone of aeration in the plume is not continuous, and the residence time will be significantly less than the estimated time above. JRB, 1984, concluded that "if the well matrix produces a non-continuous aeration zone, it will be relatively ineffective with high groundwater contaminant levels, but may be very effective with residual organic concentrations of less than 5mg/liter." (p. 4-59).

In general, as in any in situ method, inhomogeneities in the soil or in the waste composition and distribution will lead to pockets where treatment levels are low or where no reduction has occurred. Extensive testing is required to minimize this potential result.

RESOURCE REQUIREMENTS

Costs

Surface application of microorganisms is a relatively inexpensive technology. It requires the addition of microbes and maintenance of the microbial population (e.g., fertilizing, aeration, pH adjustment). Unit costs will depend on the location (surface or subsurface) and quantity of the waste to be biodegraded and the type of microbes required. Costs for developing or selecting the appropriate microbe and determining their site specific effectiveness must also be included.

The costs of a complex system based on pumping and recirculating groundwater are much higher. No data are available for complete systems. A typical system would include wells to extract and reinject groundwater, air wells, nutrients and special microorganisms, and in some configurations, a surface reactor to cleanup the extracted groundwater and produce a microorganism inoculum for reinjection.

Personnel

No special requirements.

Example

It is determined that simple, surface application of in-situ biodegradation could be used to treat the lagoon sludge at the example site. The sludge is to be excavated and spread to a one foot depth over a 1600 sq. ft. area. 100 pounds of microbes are then applied and the soil is fertilized and cultivated monthly. An additional 100 pounds of microbes are required at the end of the first year and the system is then operated for an additional 12 months. Total cost for the two years insitu biodegradation would be \$15,000.

SUMMARY

In-situ biodegradation holds promise of destroying organic wastes in place, thus obviating need for long-term containment. Some sort of containment system, consisting of pumps and drainage ditches is needed to prevent outward migration during the treatment process which may extend over many years. This technique appears to be less expensive than other methods with the same objective, for example, excavation or pump and treat on the surface. Except for expected variations in effectiveness within the treatment zone, the method can reduce contaminant levels of many species to low (ppm or less) concentrations. Experience at clean-up sites is very limited. Many organic species found at waste sites are not easily biodegraded. Such wastes include chlorinated solvents, pesticides, polynuclear aromatic hydrocarbons. Unfortunately, these often are the most toxic species present in a complex mix of waste constituents. Although

wells have been used to maintain aerobic conditions deep in the soil, in general, the effectiveness of insitu biodegradation is limited for contaminants more than two feet below the surface.

10. Extraction/In Situ Solution Mining

DESCRIPTION

Extraction involves the application of a solvent to waste-solids or sludges and collection of the elutriate for the removal and/or treatment of hazardous waste constituents. Typically solvents used are water, acids, ammonia and/or chelating agents such as EDTA, which solubilize heavy metals and other inorganic ions. As the solvent is collected a fraction can be recycled through the wastes with a makeup solution. The remainder can be treated and disposed of. Detailed information for extraction can be found in Ehrenfeld and Bass, 1983; EPA, 1982; and Arthur D. Little, 1976.

In-situ solution mining is similar to extraction except that the elutriate is collected through well points. Various methodologies for in situ solution mining are available. Descriptions of these techniques can be found in Arthur D. Little and Utah Waste Research Laboratory, 1984.

CAPABILITY

Range of Applicability

Solution mining can either be used as an insitu or as an above ground treatment (extraction). In situ solution mining involves either allowing the solution to infiltrate through the soil or injecting the solution through well points. The elutriate is then collected from the groundwater through well points. On-site extraction involves excavating the waste and placing it on an impervious liner. The solvent is then allowed to infiltrate through the wastes and the elutriate is collected via a leachate collection system.

"Organic compounds with hydrophobic functional groups become strongly attached to the soil and cannot be eluted with water. Leaching of these compounds can be enhanced using suitable polar organic solvents, mixtures of solvents, or complexing agents. Wastes with hydrophilic groups can be more easily eluted with water. Dilute acids may serve as a solvent to flush certain basic organics such as amines, and aniline surfactants may be useful in dissolving oil and grease.

"Inorganic acids may be used to dissolve basic metals, oxides, hydroxides, and carbonates. Carbon dioxide and ammonia has been used for leaching copper and nickel. Other complexing or chelation agents commonly employed may be ammonia, ammonium sulfate, citric acid, EDTA, thiourea, etc. Sodium has been used to dissolve metallic aluminum and can be used for zinc, tin, lead and other metals" (Srivastava & Hajj-Djafari, 1983).

Experience with solution mining at a hazardous waste site is limited to the Goose Farm site in Plumstead Township, New Jersey.

Effectiveness

Solution mining technology is not commercially available and experience is limited, so that technical effectiveness under field condition is not known. Research and field trials in progress, however, show substantial promise (Shrivastava and Haji-Diafari, 1983). One major uncertainty is the extent of contact of the solvent with the waste materials; that is, the fraction of the wastes that would actually be treated. The effectiveness of removal is also not well characterized. In any case, this approach is not capable, in any practical application, of removing all of the contaminants. But it would be useful in reducing gross contamination levels as the example below indicates. For in-situ systems its effectiveness will depend on the ability of the well point system to collect the elutriate. Failure of the well point system to collect elutriate could result in an increase rather than a decline of groundwater contaminant concentrations. The solvents and elutriants used to remove contaminants may themselves be toxic and, thus, must be very carefully controlled. The elutriate stream must be treated to remove the dissolved contaminants creating a serious secondary problem.

The process does not detoxify the contaminants; it only removes them from the soil or waste mass to another (presumably more easily treated stream. The overall effectiveness of the process depends on how that stream is handled. Further, some of the contaminants which originally may have been insoluble or strongly adsorbed to the soil or waste matrix may become solubilized by the treatment process and become more likely to leach out and migrate from the site than before the treatment was applied.

Experience at the Goose Farm site indicates that solution mining is potentially effective in removing wastes from the unsaturated zone. Goose Farm utilized a two-phased well point system. In Phase 1, well points were installed to the unsaturated zone and groundwater was injected into the well points under pressure, using on-off relays in order to create a pressure pulse. This served to flush the contaminants out of the unsaturated zone into the groundwater. In Phase 2, the well points were then lowered to the water table to collect the contaminated groundwater. The system was designed to remove organic contaminants from the 3-4 foot layer of clay which had a TOC concentration of 30mg/g. Bench scale testing indicated that 11 million gallons of water would be required to remove the organics from the soil layer. This is equivalent to 10 complete soil rinses of the layer. The system, however, was shut down after only 7.8 million gallons were injected. The decision to shut down the injection wells before the 11 million gallon mark was reached seems to have been based on factors other than technical judgement. Sampling data indicate that decontamination of the soil may have been incomplete. The same data, however, indicate that partial flushing did occur and suggest

that continued flushing might have resulted in the intended level of decontamination. Additional field experience with solution mining is required before long-term effectiveness can be assessed.

Reliability

There are inadequate data to assess the potential reliability of this method. Complete removal depends on contacting the entire contaminated mass with the solvent. Inhomogeneities and fissures in the soil strata being treated would complicate flow patterns and in many cases would make full contact difficult, if not impossible to achieve. Extensive surveys would be required prior to operations; monitoring would be required during and after operations to determine the success of the technique.

RESOURCE REQUIREMENTS

Costs

Costs for in situ solution mining are similar to those for groundwater pumping. The major additional cost would be for the solvent distribution system and the solvent itself. Chemical solvents might cost from \$50 to \$250 per ton.

For extraction (or onsite solution mining) the cost of excavation and construction of a leachate collection system are the significant cost items. Chemical costs would be the same and well points would not be required.

Personnel

No special requirements.

Example

It is assumed that the sludge lagoon at the example site could be treated by solution mining, and that 4000 tons of 20% hydrochloric acid would be required.

For the in situ option, the lagoon is flooded with acid and the elutriate collected via 5 well points. Costs for this system, not including elutriate treatment or disposal is \$400,000.

For the onsite option, sludge is removed from the lagoon to allow for installation of a synthetic liner and leachate collection system. The sludge is then returned to the lagoon and flooded with acid. Cost for this system, not including elutriate treatment or disposal, is also about \$400,000.

In both cases, substantial (perhaps significantly larger) costs would be added for the system required to treat the elutriate.

SUMMARY

This method, although largely untried, has potential to remove contaminant from soil. It serves as a potential alternative to containment through barriers, stabilization, or excavation. Notwithstanding serious concerns about the completeness of removal, it can permanently remove a source of offsite migration. But some means of treatment and disposal of the contaminants transferred to the elutriate would be required as a tradeoff. Precipitation of metals and landfilling of the sludge is a likely choice for inorganics. Biological or thermal methods would destroy organics without requiring disposal.

11. In Situ Leachate/Groundwater Treatment

DESCRIPTION

Several techniques are available to treat contaminated leachate or groundwater in place. Two principal variations are:

- o permeable treatment beds - this approach uses trenches filled with a reactive permeable medium to act as an underground reactor (see Figure 29). Contaminated groundwater or leachate entering the bed reacts to produce a non-hazardous soluble product or a solid precipitate.
- o chemical injection - this process entails injecting chemicals into the ground beneath the waste (see Figure 30) to neutralize precipitate or destroy the leachate constituents of concern.

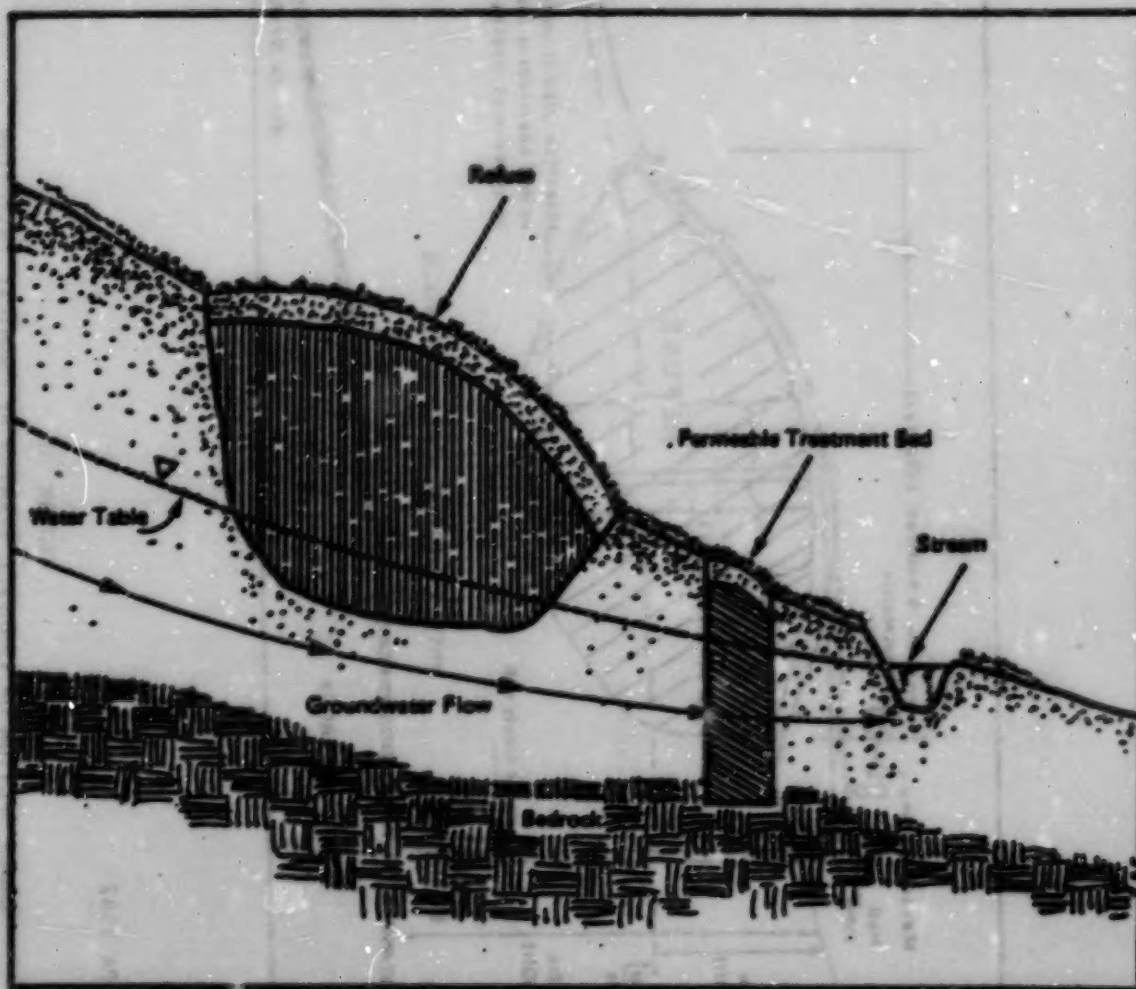
Detailed descriptive information on in situ leachate/groundwater treatment can be found in EPA, 1982, and Ehrenfeld and Bass, 1983.

CAPABILITY

Range of Applicability

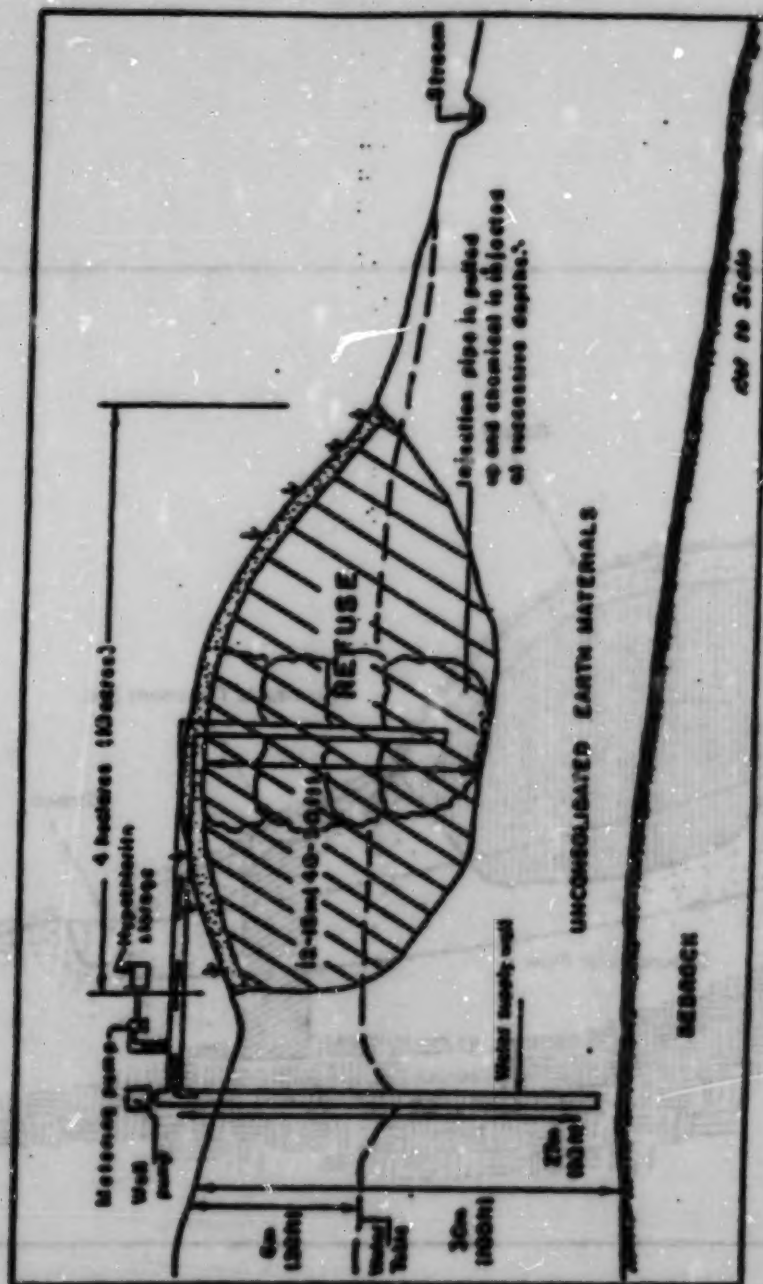
Permeable treatment beds are applicable in relatively shallow aquifers since a trench must be constructed down to the level of bedrock or impermeable clay. Permeable treatment beds are often only effective for a short time as they lose reactive capacity or become plugged with solids. When this occurs the spent materials must be replaced with fresh reagents and be disposed of if necessary. The materials used for this form of treatment include:

- o Limestone and crushed shell - limestone neutralizes acidic groundwater and may remove metals such as iron and chromium. Extrapolated bench scale data indicate the contact time needed to change the pH of the groundwater.



Source: EPA 1982

FIGURE 29
INSTALLATION OF A PERMEABLE TREATMENT BED



Source: EPA 1982

FIGURE 30
CROSS SECTION OF LANDFILL TREATED BY CHEMICAL INJECTION

- o Activated carbon - activated carbon removes non-polar organic contaminants such as CCl_4 , PCBs, and benzene.
- o Glauconitic green sand - bench scale studies indicate removal efficiencies of greater than 90% for As, Cu, Hg and Ni, and 60-89% for Al, Cd, Ca, Cr, Co, Fe, Mg, Mn and Zn for retention times on the order of several days.
- o Zeolites and synthetic ion exchange resins - these materials may be effective in removing solubilized heavy metals.

Chemical injection is a conceptual technology. The areal spread and depth of the leachate plume must be well characterized so that injection wells can be placed properly to intercept all the contaminated groundwater.

Effectiveness

The removal efficiency associated with in situ leachate/groundwater treatment is difficult to estimate since the technology has not been demonstrated in the field. Secondary effects may include producing new hazardous compounds by reaction of the permeable treatment bed or injected chemicals with waste constituents. Also most of the systems above capture the contaminants within the reactive materials. At some time these materials would have to be removed and treated or disposed of in order not to re-release the contaminants into clean groundwater.

Reliability

The reliability of in situ leachate/groundwater treatment has not been demonstrated in the field. The performance depends on intercepting and controlling the contaminated groundwater flow. This may be difficult to accomplish during periods of high rainfall or seasonal changes in the water table. Designing the treatment bed to obtain uniform and predictable performance may be difficult due to expected variability of groundwater flow in and out of clean-up sites.

RESOURCE REQUIREMENTS

Costs

Costs for permeable treatment beds would be similar to those for subsurface drains. The major difference is that the trench is filled with the treatment medium rather than drainage material.

Costs for chemical injection would be similar to the costs for solution mining. The major difference is that the chemicals are injected into the waste rather than allowed to infiltrate through the waste. The chemicals used would also be different.

No data is available on cost for these technologies at actual sites.

Personnel

No special requirements.

SUMMARY

In situ treatment, although untested at clean-up sites, could permanently remove both inorganic and organic contaminants from flowing groundwater. No pumping is required as for many aboveground systems. The technique would be most useful in treating shallow aquifers or leachate plumes. Extensive testing to determine the appropriate reagent and trench dimensions would be required. The technique appears most useful in treating short-term groundwater or leachate problems where more conventional systems such as pump and treat (carbon adsorption) would require elaborate and expensive capital equipment. Except for a few combinations of waste and reagent, the treatment bed will become loaded with the hazardous materials or their potentially hazardous reaction products. These spent materials must be removed, and be treated or disposed of to achieve a long-term solution for the clean-up site.

III. COMPARATIVE ANALYSIS OF CLEAN-UP TECHNOLOGIES

A. Applicability of Technologies at Specific Sites

The selection of the preferred technology or set of technologies at a site depends on the characteristics of the site, the composition and distribution of hazardous materials, the technical characteristics of the technologies, the costs of the technologies, and the nature of the selection process mandated by regulation and other institutional factors. This portion of the report develops a comparative analysis of the several technologies presented above from the perspective of these several factors. Such an analysis is complicated by the extraordinary degree of variability among cleanup sites. Although many of the sites presently on the National Priority List and others that have been identified by Federal or State agencies share common problems, literally every single site is unique. The selection process established under the National Contingency Plan and by state regulations and guidelines reflects this premise and includes many data gathering and analytic steps that are designed to select the technologies most appropriate for the individual site according to the various criteria in the selection process.

But in spite of this high degree of variability in site characteristics and individuality of appropriate solutions, there are a number of general features that differentiate the major categories of technologies and the individual technical approaches within each of those categories. In considering the analysis that follows, the reader should recognize that exceptions to almost every general statement will undoubtedly occur. Costs are particularly sensitive to specific site characteristics, and the relative cost advantages between two approaches may exhibit contrary behavior at sites of different nature.

The technologies have been, as noted above, been rather arbitrarily classified as containment or treatment. In reality there are shades of differences within each of these categories. Further, clean-up actions tend to apply combinations of technology. It would be more realistic to describe actions at a site as ranging from predominantly containment to predominantly treatment, rather than a sharp either/or situation. Several examples of activities at actual sites were selected to elucidate this point further, and to temper the theoretical evaluative framework with experience.

Selecting appropriate examples of the application of a wide range of clean-up technologies is a difficult task. Much of the early activity at Federal Superfund, state managed, and private action sites has emphasized removal and initial or temporary remedial actions. Much of the effort being expended currently has been directed toward the investigation of conditions at sites, the study of potential technological approaches, the selection of the preferred approaches, and their design. Nonetheless, there is a scattering of sites where

remedial action technologies have actually been applied and for which there is sufficient operating experience on which to draw some judgments as to the degree to which the technologies have achieved the functions for which they were designed. Some of these sites have been chosen as case examples and are described in Table 5.

Referring to the examples as specific applications, Cases No. 1 and No. 2 illustrate the use of containment techniques solely. Case No. 1 uses one of the simplest of all containment techniques, some sort of cap over the site. Caps are used either to prevent rainwater and surface run-on from infiltrating into the site, or to prevent escape of contaminants into the atmosphere. The principle function in Case No. 1 was the latter, to prevent the release of asbestos particles into the air in a populated area. This case indicates that even this relatively simple technology is subject to potential failures. Case No. 2 also is an application of capping. Here the principal purpose was to prevent infiltration and subsequent contamination of groundwater by very soluble cyanides present at the site. A surface water diversion system was also included to reduce the likelihood of further groundwater contamination. This example also contains reference to another technology, alternative water supply, which may be used during times while some permanent technologies are being installed, or in cases where alternative technological solutions are considered infeasible. This approach to remedial action is not considered in this analysis.

The remaining case studies are all examples of combinations of treatment technologies and containment technologies. Case No. 3 represents an excellent example of the application of a wide variety of technologies working in tandem. A cap was installed to reduce infiltration. A barrier, utilizing slurry wall technology, has been installed completely around the site. Groundwater flow interception through a series of wells controls migration of the contaminant plume itself. At present, the groundwater is recirculated upgradient of the contaminated zone, while treatment processes are being installed. One treatment process will remove metals from the contaminated groundwater by chemical precipitation, and settling. Volatile organics will be stripped from the groundwater and fed to a thermal destruction unit. A portion of the stripped groundwater will be fed to a biological treatment plant and recharged upgradient. This stream will act as a flushing medium to remove the contamination already present in the zone underneath the site. All principal containment and treatment approaches are in use or are planned to be in use at this site.

TABLE 5

EXAMPLES OF CLEAN-UP TECHNOLOGIES AT EXISTING SITES

CASE NO. 1

Name: Mountain View Mobile Home

Location: Arizona

Date Construction completed: 1983

Problem: Mobile home park located over asbestos tailings fill caused air pollution

Treatment Measures: None

Containment Measures:

- 1981
 - o decontamination of homes
 - o 6 inch cap of clean soil failed
- 1983-84
 - o demolished all homes
 - o 21 inches of compacted soil and 3 inches of coarse soil for erosion control

TABLE 5

EXAMPLES OF CLEAN-UP TECHNOLOGIES AT EXISTING SITES
(continued)

CASE NO. 2

Name: Kaiser Aluminum Mead Works

Location: Washington

Date: Construction Completed: 1980

Problem: Groundwater contamination with cyanide from old pot liners
abandoned on site

Treatment Measures: None

Containment Measures:

- o consolidate all pots in one area
- o asphalt cap
- o surface water diversion
- o alternative water supply for neighbors

TABLE 5

EXAMPLES OF CLEAN-UP TECHNOLOGIES AT EXISTING SITES
(continued)

CASE NO. 3

Name: Sylvester's

Location: New Hampshire

Date Construction Completed: 1982 slurry wall and groundwater
recirculation
in progress - groundwater treatment

Problem: Illegal dump in old sand borrow pit caused extensive
groundwater and soil contamination

Treatment Measures:

- o metals removal
- o packed towers air stripping with thermal destruction of fumes
- o recharge of effluent within containment area for flushing
- o To maintain a gradient toward the containment area a small portion of air stripper effluent will be diverted to an on site biological treatment plant for recharge outside of containment area

Containment Measures:

- o slurry wall to fractured bedrock (enclosing 20 acres)
- o cap (30 mm plastic; 18" top soil, grading and vegetation)
- o groundwater interception and upgradient recharge (temporary until groundwater treatment system is on line)

TABLE 5

EXAMPLES OF CLEAN-UP TECHNOLOGIES AT EXISTING SITES
(continued)

CASE NO. 4

Name: Goose Farm

Location: New Jersey

Date: Construction completed: 1980

Problem: Abandoned hazardous waste dump originally for drums and bulk liquids. Local ground water and a stream on site were contaminated with organic chemicals (currently being studied as a superfund site to evaluate extent of remaining contamination).

Treatment Measures:

- o treatment of ground water by carbon adsorption and air stripping
- o recharge and flushing of groundwater by spray irrigation

Containment Measures:

- o removed waste
- o removed contaminated soil

TABLE 5

**EXAMPLES OF CLEAN-UP TECHNOLOGIES AT EXISTING SITES
(continued)**

CASE NO. 5

Name: General Electric

Location: California

Date: Construction completed: 1981

Problem: Soil contaminated with PCBs and petroleum products as a result of over 40 year of production and repair of transformers. Some limited groundwater contamination was found

Treatment Measures:

- o oil/water separation
- o water from separator is discharged to POTW
- o waste oil and sediments to class I landfill

Containment Measures:

- o groundwater interceptor drain
- o soil-bentonite cap with gravel cover
- o surface water diversions

TABLE 5

**EXAMPLES OF CLEAN-UP TECHNOLOGIES AT EXISTING SITES
(continued)**

CASE NO.6

Name: Stroudsburg Gas Co.

Location: Pennsylvania

Date Construction Completed: 1982

Problem: An estimated 1-2 million gallons of coal tar from a coal gasification plant had been injected into nine wells over a 60 year period. Coal tar migrated to a stream bed causing serious surface water contamination

Treatment Measures:

- o filter fences

Containment Measures:

- o inverted dams
- o grout curtain
- o slurry cut off wall
- o coal tar recovery well

TABLE 5

**EXAMPLES OF CLEAN-UP TECHNOLOGIES AT EXISTING SITES
(continued)**

CASE NO. 7

Name: Bruin Lagoon

Location: Pennsylvania

Date Construction Completed: in progress

Problem: Closure of a one acre lagoon filled with 35,000 cu yd asphaltic sludge and 500,000 gal of acidic liquid. Spills of acidic liquid had caused fish kills and threatened water supplies

Treatment Measures:

- o solidification in situ with kiln dust

Containment Measures:

- o removal of liquid to industrial wastewater treatment plant
- o cap (geotextile, clay-bentonite, filter cloth, 18 inches of topsoil)

TABLE 5

**EXAMPLES OF CLEAN-UP TECHNOLOGIES AT EXISTING SITES
(continued)**

CASE NO. 8

Name: Biocraft

Location: New Jersey

Date Construction Completed: 1981

Problem: Leak in underground chemical feed line resulted in solvent contamination of groundwater and surface water

Treatment Measures:

- o aerobic biological treatment and reinjection of groundwater
- o aeration of soil with in situ continuous aeration wells

Containment Measures:

- o replacement of broken chemical feed lines with above ground lines
- o interceptor drain
- o excavation and disposal of contaminated soil off site

Case No. 4 illustrates one of the more common treatment techniques for groundwater, carbon adsorption. This technology is potentially capable of reducing contamination of many organic species to levels consistent with drinking water criteria. In this example, recharge and continued flushing is accomplished by spraying the treated groundwater on the surface of the soil rather than reinjecting it directly through wells as in the previous case.

Case No. 5 illustrates a combination, again, of several containment methods. In particular, it illustrates yet another means of arresting the groundwater flow, the use of an interceptor drain system. The treatment method used here is a physical one, involving the separation of oil from the collected groundwater.

Case No. 6 illustrates a rather unique situation in which contamination was present in a surface stream rather than a groundwater source. A variety of containment measures were used to arrest further contamination of the stream bed. A filter fence consisting of pads of filtration material were placed in the stream to remove droplets of coal tar from the flowing waters.

Case No. 7 is an example of an in-situ solidification process. In this example, kiln dust was used to solidify residual sludges in the lagoon. This treatment immobilized some of the waste constituents and provided sufficient physical integrity to permit installation of a cap over the lagoon.

The last example, Case 8, utilizes a novel in-situ biological treatment approach to decontaminate groundwater containing a number of organic pollutants. The system includes an above-ground biological reactor with reinjection of the treated groundwater. The process continues within the soil by maintaining aerobic conditions through the use of aeration wells. This is a privately managed site. The limitations on the application of novel techniques in the Federal selection process did not apply in this case.

These examples show that single, isolated clean-up technologies, as described in the preceding section are rarely used at actual sites. In almost every case combinations of technological approaches are used. The combinations may be formed on several bases:

- 1) Containment and treatment methods may be used conjunctively.
- 2) Some treatment and disposal processes may be used in succession for isolation of the contaminants, for reduction of their volume, and for detoxification and disposal.
- 3) Different treatment techniques may be used for distinct wastes at the site or for distinct components within a waste.

- 4) Combinations of containment methods may be used to obtain levels of performance not attainable through any single technique.

Table 6 represents a summary of the applicability of the individual technologies to different types of remediation problem, as defined by the waste type. The table shows the following type of problems:

- o Contaminated groundwater
- o Contaminated soil
- o Ponded aqueous liquids
- o Ponded organic liquids
- o Ponded sludges
- o Drummed wastes
- o Treatment residues

In addition, technologies applicable to primarily organic, inorganic, and mixed wastes are noted. Those technologies that may be used alone (but generally are used in combinations) are indicated by "X". Those technologies that are always (or nearly so) used in combinations and process trains are indicated by "O". Situations where the applications may be limited by interferences between waste components are marked with an "I". Finally, applications which are technically possible but unlikely compared to other choices are indicated with a "?".

As noted earlier, the treatment processes include two major types, (1) those that detoxify the hazardous contaminants, and (2) those that transfer the contaminants from one medium to another. The former type may be used alone, for example, incineration of organic liquids. The residue from this process, if any, may be disposable in conventional landfills. On the other hand, the incineration of soils will leave a large residue that may still require disposal in landfills. Landfills have been included in the table for this reason, but have not been discussed in the previous chapter.

The process train can become very complex and expensive to operate and produce large volumes of residues requiring disposal. Carbon adsorption is a transfer process and always requires some additional process steps. Regeneration (thermal oxidation) is often used to destroy organic contaminants that have become adsorbed. Alternatively, the spent carbon may be landfilled. In some very complex settings, fume incineration may be used in conjunction with regeneration to destroy volatile species that are released during the regeneration process.

Examination of Table 6 shows that each technology may have a different kind of applicability for different types of wastes.

TABLE 6

CLEAN-UP TECHNOLOGY APPLICABILITY MATRIX

Type of Remediation Problem	Containment Technologies										Treatment Technologies														
	Surface Soils	Run-on Contaminants	Particulates (4)	Particulates (5)	Leachate (5)	Solidification	Encapsulation	Volatilization	Landfill	Removable Residue	Solution Mining (6)	In-Situ Treatment	In-Situ Remediation	Biological Treatment	Chemical Red/Ox (7)	Thermal Oxidation	Incineration	Neutralization	Fluoridation/Alumina	Ion Exchange	Neutralization	Carbon Adsorption	Air Stripping	Advanced Oxidation	Advanced Oxidation
Contaminated Groundwater																									
Organic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Inorganic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mixed	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Contaminated Soil																									
Unsaturated Zone	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Saturated Zone	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Partial Aqueous Liquids																									
Partial Organic Liquids	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Partial Solids	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Organic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Inorganic/Mixed	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Partial Solids																									
Partial Solids	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Treatment Facilities																									
Partial Solids	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

See Groundwater For Appropriate Treatment Technologies.

See Partial Solids For Appropriate Treatment of Contaminants.

Notes:

(1) Includes Photolysis.

(2) Neutralization may be only step needed for corrosive wastes.

(3) May require solidification prior to disposal.

(4) May be used alone, often in combination with surface seals, pumping and treatment.

(5) Must treat extracted well water or sludge by appropriate treatment.

Legend:

X - Technology that may be used independently.

O - Always used in combination with other technologies.

Y - Possible but uncommon use of technology.

I - Possible interferences in mixed wastes.

Applicability, based only on waste types is insufficient to indicate which choices are appropriate. Site factors play a very important role. But site factors are difficult to generalize in a useful manner with respect to developing fairly simple matrix tables such as that shown. Site factors are very important in selecting the containment techniques. For example, barriers are not applicable to sites where bedrock or impermeable clay lies at a depth which exceeds the capability of the technique.

The particular combination that is best for a specific site is not, in general, so clear that it pops up out of a table such as developed herein. The Federal and related state (and private) remedial action selection procedures reflect this characteristic. Most work through a process which begins with a large list of potential system configurations and narrows down the list using technical criteria to arrive at the one system (in some cases, the few systems) that provide the most effective solution at the least cost.

B. Individual Containment Technologies

This section compares the various containment technologies generally as if they were used alone. The presentation below should be read with respect to the several caveats presented earlier that express the difficulty in generalizing.

The salient features of the various containment technologies are summarized in Table 6-A. Table 6-A displays advantages, disadvantages, and limitations for each of the several technologies.

Barriers have been widely utilized in cleanup actions to date. All of the barrier techniques methods have the potential to stop or substantially reduce contaminant migration quickly. All, except for block displacement, require that there be an impervious layer underlying the site at some depth within the range for which the technology is applicable. This situation is not found at many sites. The layers underlying the source of contamination are often fractured providing potential pathways for contaminants to bypass the barrier. This potential problem can be alleviated by use of bedrock grouting, a technique which, in essence, fills up the pores and fractures with a plastic or plaster-like substance. But bedrock grouting is expensive, difficult to apply in many situations, and is of uncertain effectiveness.

Slurry walls are the most commonly used of the several types of barriers. This technique has been used in general construction practices to dewater sites and has been used on a number of hazardous waste cleanup sites as well. It is versatile and can be used in a wide variety of soil and geologic settings. Applications of grout curtains are limited compared to slurry walls. They can be used only at sites with characteristics in the range of soil conditions over

TABLE 6-A

CONTAINMENT TECHNOLOGIES - SUMMARY

<u>Technology</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Limitations</u>
<u>Grout Curtain Barriers</u>			
- Slurry Wall	Most versatile, best understood barrier technology. Can be inexpensive compared to other barrier techniques Low O&M	Requires excavation Requires site area to mix backfill. Difficult to verify continuity of slurry or backfill. Difficult to key to bedrock.	Must tie to impervious zone Not 100% impermeable Long-term effects of some chemicals on permeability uncertain.
- Grout Curtain	Minimal site disturbance. No excavation required. Low O&M	Chemicals in the grout may cause site safety or environmental problems. Difficult to verify continuity of wall. Limited applicability. Expensive compared to other barriers. Difficult to key to bedrock.	Less than 20% soil can pass No. 200 sieve. Must tie to impervious zone. Not 100% impermeable. Long-term effects of some chemicals on permeability uncertain.
- Vibrated Beam	Special slurries improve chemical compatibility. No excavation required. Low O&M	Very sensitive to construction quality. Difficult to verify continuity of wall. Difficult to key to bedrock. Relatively new technology.	No obstructions in soil. Must tie to impervious zone. Access for large cranes needed. Not 100% impermeable. Long-term effects of chemicals on permeability uncertain.

TABLE 6--A

CONTAINMENT TECHNOLOGIES - SUMMARY
(continued)

Technology	Advantages	Disadvantages	Limitations
- Sheet Pile	No excavation required. Low O&M	Expensive Difficult to key to bedrock. Continuity of wall at joints difficult to verify.	Soils must be loosely packed. Limited to about 50 ft. Must tie to impervious zone. Not 100% impermeable. Some chemicals may attract piling material.
- Block Displacement	No underlying impervious zone needed.	Technology under development. Continuity is difficult to verify.	Site conditions must conform to complex design requirements.
<u>Groundwater Pumping</u>			
- Well Points	Proven and well understood. Can function for very long periods. High design flexibility. High reliability. Useful in many situations. Effectiveness can be verified.	Design may require expensive modeling. Long-term O&M required. Performance sensitive to design. Collected liquid must be treated or disposed of.	Useful up to 10 meters. Will not affect contaminants in unsaturated zone or which do not flow.
- Deep Well Systems	Same as well points.	Same as well points.	Same as well points; except useful to any depth.

TABLE 6-A

CONTAINMENT TECHNOLOGIES - SUMMARY
(continued)

<u>Technology</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Limitations</u>
<u>Subsurface Drains</u>	Proven and well understood. Low O&M Superior to wells under certain conditions. Less sensitive to design than wells. Conceptually simple.	Less flexibility than wells. Susceptible to clogging. Excavation required. Collected liquid must be treated or disposed of.	Difficult to install beneath waste site. More cost-effective in shallow applications.
<u>Runon/Runoff Controls</u>	Proven and well understood. Inexpensive. Effectiveness desirable. Only conceptual design required.	Periodic inspection and maintenance required.	May not be able to handle abnormal storms.
<u>Surface Seal/Caps</u>	Inexpensive compared to excavation and removal. May be used as an interim measure where surface infiltration is a problem.	Periodic inspection and maintenance required.	Difficult for very large sites, or if obstructions are present. Subject to potential failure, without proper design, installation and maintenance.

TABLE 6-A

CONTAINMENT TECHNOLOGIES - SUMMARY
(continued)

<u>Technology</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Limitations</u>
<u>Solidification and Stabilization</u>	Improves containment performance. High short-term effectiveness possible. Waste material (e.g. fly ash, kiln dust) can be used as pozzolan.	Extensive testing may be required. Many processes developmental.	Long-term integrity uncertain. Not useful for many organics.
<u>Encapsulation</u>	Improves effectiveness of land disposal.	Developmental	Long-term integrity uncertain. Requires solidification of bulk wastes.
<u>Vitrification</u>	No excavation required.	Technology under development.	Site conditions must conform to narrow range of site and waste characteristics.

which this technique can be applied. The technique is considerably more expensive than slurry wall technology. But it has been used in special situations where excavation would be unfeasible, precluding the use of slurry walls.

Vibrated beam techniques are relatively new and share the advantage of grout curtains in that no excavation is required. There is a great deal of interest in this emerging technology and its use is being considered at a number of cleanup sites. Although not as versatile as conventional slurry walls, the technique can be employed over a wide range of site conditions. Special equipment and specially trained field personnel are required. Only a few contractors possess the experience and equipment at present.

Sheet piles, a common barrier technique in general construction practice, is less attractive than the first three techniques discussed above. It is an expensive technique and can be employed only when depth to bedrock is less than about 50 feet. The long-term stability of piling materials in contact with contaminated soil is unknown. In conventional applications, piles are generally removed at the end of the construction project.

The last of the barrier techniques, block displacement, is developmental at present. This technique has the advantage relative to all the others that it does not depend on the presence of an underlying impervious layer as it, in essence, creates its own. At least at its present stage of development, it requires sites with very special characteristics that conform to its design limitations.

None of the barrier techniques can provide completely impermeable containment, reliably over long periods of time. The barriers all have some finite permeability but, if properly installed in favorable settings, they will result in very low levels of migration relative to the indigenous soils. It is difficult to verify the continuity of a barrier. The presence of voids, or cracks, or gaps will permit leakage. In large sites, the expectation of discontinuities is quite high. Also, if used in conjunction with pumping, outward migration may be prevented (see below).

Groundwater pumping can be used as an alternate to barriers to prevent outward movement of a contaminated flow. Pumping may also be used as a complementary technology in combination with barriers to improve the containment performance of the overall system or to extract contaminated fluids for treatment. If a pumping system is properly designed and installed, outward groundwater flow can be prevented for as long as the system operates. Thus, even for barriers with finite permeability, contaminants should be contained. Continuous pumping is required except for short periods for maintenance. If for any reasons the pumps would be shut down for long periods of time, the plume would revert to its outward migration pattern and eventually would move beyond the zone of influence of the pumps. Thus, as long as the original source of contamination remains, a hydraulic containment system will have to remain in active operation.

The costs of hydraulic systems, as a consequence, can be quite high over the long term although initial costs are relatively low. Extensive and expensive testing and modeling may be required as part of the design. The design of a hydraulic system is very sensitive to individual site parameters, such as the extent of contamination, groundwater flow patterns, geological characteristics, rainfall, and similar parameters. Skilled groundwater hydrogeologists are needed to design the test program, analyze the test data, and prepare the design for the groundwater pumping system. The water extracted by pumping may require treatment prior to discharge if contaminant levels exceed permit limitations.

Subsurface drains is a conventional and widely used method for cutting off groundwater flow. Drain systems are generally inexpensive but the rigors of field operations at a cleanup site will increase the cost of this technology. Drains are most useful in shallow applications and may be the most cost effective of all the containment approaches under these circumstances.

The next two technologies, Runon/Runoff Controls and Surface Seal/Caps are designed to prevent infiltration of surface water into the site. Runon/runoff controls use conventional approaches that require little or no modification for application at hazardous waste sites. Appropriate controls can be designed for virtually any site conditions and environmental setting. Some form of runon/runoff control is found at most cleanup sites.

Surface seals and caps have been and are expected to be widely used. In regions where the principal factor influencing offsite migration is surface infiltration, caps can, by themselves, act to contain the contamination. The technology is inexpensive compared to excavation and removal and has been used specifically as an alternative to removal. Capping prevents contact with contaminated soils at the surface, and thus, may permit post-closure use of the site if appropriate. Caps can be installed quickly and require a minimum of design and testing and have been used as interim measures to reduce migration rates while other measures are being considered or implemented. But caps can fail (see Case #1, above) and must be properly designed, installed, and maintained.

The above techniques act to contain the contaminants in a macroscopic manner, that is, to prevent flow through the boundaries of the contaminated region. Solidification and stabilization, and Vittrification function by containing the wastes on a microscopic level, that is, to bind the waste within a matrix so tightly that leaching into groundwater flowing through the site will cease. Long-term effectiveness of solidification techniques over many years is at present poorly understood, although data indicate that these techniques are very effective in immobilizing contaminants under controlled conditions. These techniques have not been in use long enough to get data from actual field operations. Waste characteristics at cleanup sites are variable and do not conform to

the conditions for which many of the techniques were developed initially. Vitrification is a developmental process designed initially for immobilizing radioactive wastes. Its major advantages are that it can theoretically bind certain wastes permanently in a glassy matrix in an *in situ* mode.

Combinations of solidification or encapsulation would improve the overall performance of barrier containment systems and perhaps could provide system integrity over very long time periods. The techniques would add cost to the basic containment system and would be justified only if the added reliability and performance is worth the additional cost.

C. Individual Treatment Technologies

The key features of treatment technologies are shown in Table 7. Treatment technologies rely on several principles to destroy the wastes, convert them into nonhazardous forms, or transfer them from one medium to another. All of the techniques have some limitations with respect to the types of wastes they can handle. They break down roughly into two classes; techniques for organic contaminants such as benzene or methylchloride, and techniques for inorganic compounds such as mercury chromium, or cyanide compounds. Most are designed to treat aqueous wastes. The list also contains technologies to treat gaseous streams and solids such as contaminated soils or sludges.

The various techniques are differentiated in their mode of action. Many work on aqueous streams, either groundwater or the extract produced by contacting contaminated materials with some sort of solvent. A few are designed to operate *in situ*, that is, directly on the wastes in place.

Technologies such as biological treatment, thermal destruction and incineration, wet air oxidation, and *in situ* biodegradation act to destroy the hazardous organic contaminants present in the wastes. The process for cyanide, an example of chemical oxidation, behaves similarly; cyanide compounds are destroyed. Other treatment processes for organics transfer the materials from the treated stream to another medium. Stripping and carbon adsorption represent this type of technology. While this type of process may be quite effective in cleaning up the major potential source of exposure, some additional means of treatment or disposal may be required to eliminate the overall hazards. Combinations of techniques may be used. One relatively common configuration employs biological treatment as an inexpensive means of reducing gross organic contamination by 90% or more. But because this approach cannot achieve ultrahigh removal efficiencies and may leave certain hazardous compounds untouched, carbon adsorption is often used as a second treatment step. This technique is capable of high removal efficiencies and can, in theory, produce an effluent capable of meeting drinking water standards. The

TABLE 7

TREATMENT TECHNOLOGIES - SUMMARY

<u>Technology</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Limitations</u>
<u>Destruction/Detoxification Processes</u>			
<u>Biological Treatment</u>			
- Conventional	Applicable to many organic waste streams. High total organic removal. Inexpensive. Well understood and widely used in other applications.	May produce a hazardous sludge which must be managed. May require pre-treatment prior to discharge.	Micro-organisms sensitive to oxygen levels, temperature, toxic loading, inlet flow. Some organic contaminants are difficult to treat. Flow and composition variations can reduce efficiency.
- In-Situ Biodegradation	Destroys waste in place.	Limited experience. Extensive testing may be required. Containment also required.	Aeration difficult to depths greater than two feet. Many common organic species not easily biodegraded. Needs proper combination of wastes and hydrogeological characteristics. Obtaining proper mix of contaminants, organisms, and nutrients. Organisms may plug pores.

TABLE 7

TREATMENT TECHNOLOGIES - SUMMARY
(continued)

<u>Technology</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Limitations</u>
<u>Chemical Treatment</u>			
- Wet Air Oxidation	Good for wastes too dilute for incineration or too concentrated or toxic for biological treatment.	Oxidation not as complete as thermal oxidation or incineration. May produce new hazardous species. Extensive testing is required. High capital investment. High level of operator skills required. May require post-treatment.	Poor destruction of chlorinated organics. Moderate efficiencies of destruction (40-90%).
- Chlorination for CM	Essentially complete destruction. Well understood and widely used in other applications.	Specialized for CM.	Interfering waste constituents may limit applicability or effectiveness.
- Ozonation	Can destroy refractory organics. Liquids, solids, mixes can be treated.	Oxidation not as complete as thermal oxidation or incineration. May produce new hazardous species. Extensive testing is required. High capital investment; high O&M.	Not well understood.

TABLE 7

TREATMENT TECHNOLOGIES - SUMMARY
(continued)

<u>Technology</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Limitations</u>
- Reductive for Chromium	High destruction. Well understood and widely used in other applications.	Specialized for Cr.	Interfering waste constituents. may limit applicability or effectiveness.
- Permeable Treatment Beds	Limited excavation re- quired. Inexpensive.	Developmental. Periodic replacement of treatment media required. Spent treatment medium must be disposed of.	Best for shallow plumes. Many reactants treat a limited family of wastes. Effectiveness influenced by groundwater flow variations.
- Chemical Injection	Excavation not required. No pumping required.	Developmental. Extensive testing required.	Best for shallow plumes. Need fairly homogeneous waste composi- tion.
<u>Incineration</u>			
- Conventional Incineration	Destroys organic wastes (99.99%).	Disposal of residue required. Test burn may be re- quired. Skilled operators re- quired. Expensive.	

TABLE 7

TREATMENT TECHNOLOGIES - SUMMARY
(continued)

<u>Technology</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Limitations</u>
- On-Site	Destroys organic wastes (99.99%). Transportation of wastes not required.	Disposal of residue required. On-site feedstock preparation required. Test burn may be required. Skilled operators required. Expensive.	Mobile units have low feed rate.
- Thermal Oxidation for Gases	Proven technology. High destruction efficiencies. Applicable to most organic streams.	May require auxiliary fuel. O&M cost can be high.	
<u>Separation/Transfer Processes</u>			
<u>Chemical</u>			
- Neutralization/Precipitation	Wide range of applications. Well understood and widely used in other applications. Inexpensive.	Hazardous sludge produced.	Complexing agents reduce effectiveness.
- Ion Exchange	Can recover metals at high efficiency.	Generates sludge for disposal. Pretreatment to remove suspended solids may be required. Expensive.	Resin fouling. Removes some constituents but not others.

TABLE 7

TREATMENT TECHNOLOGIES - SUMMARY
(continued)

<u>Technology</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Limitations</u>
<u>Physical Treatment</u>			
- Carbon Adsorption for Aqueous Streams	Well understood & demonstrated. Applicable to many organics that do not respond to biological treatment. High degree of flexibility in operation and design. High degree of effectiveness.	Regeneration or disposal of spent carbon required. Pretreatment may be required for suspended solids, oil, grease. High O&M cost.	Many inorganics, some organics are poorly adsorbed.
- Carbon Adsorption for Gases	Widely used, well understood. High removal efficiencies.	High capital and O&M costs.	More effective for low molecular weight, polar species. Disposal or regeneration of spent carbon required.
- Flotation, Sedimentation and Filtration	Low cost. Well understood.	Generates sludge for disposal.	
- Stripping	Well understood and demonstrated.	Air controls may be required.	Applicable only to relatively volatile organic contaminants.

TABLE 7

TREATMENT TECHNOLOGIES - SUMMARY
(continued)

<u>Technology</u>	<u>Advantages</u>	<u>Disadvantages</u>	<u>Limitations</u>
- Flotation	Well understood and demonstrated. Inexpensive.	Generates sludge for disposal.	
- Reverse Osmosis	High removal potential.	Generates sludge for disposal. Pretreatment to remove suspended solids or adjust pH may be required. Expensive.	Variability in waste flow and composition affects performance.
- Extraction	Greater control possible than with solution mining. Avoids disposal of contaminated soil.	Excavation and liner construction required. Collection and treatment of elutriate required.	Treated soils may still contain unacceptable levels of contaminants.
- Solution Mining	Removes contaminants from unsaturated zone. Excavation not required.	Collection and treatment of elutriate	Treatment is non-uniform and may bypass regions of contamination.

spent carbon ends up containing these residual hazardous compounds and may be regenerated thermally in which process the residuals are destroyed, or may be disposed of by incineration or in a secure landfill.

The case is quite different for most inorganic contaminants. Unlike organic compounds whose toxicological properties are derived from the arrangement of the atoms in the molecule, the hazards in inorganic compounds often come from the elements themselves, particularly in the case of heavy metal compounds. In a few cases it is possible to alter the toxicological properties by altering the valence or oxidation state of the element. Chromium in its highest valence state as chromium VI is quite hazardous but is much less toxic in a lower valence state as chromium III. Treatment with reducing agents will effectuate this transformation.

In most cases such a chemical transformation is not possible and the hazardous inorganic pollutants must be removed from the contaminated stream. Precipitation followed by settling or filtration removes heavy metal and other inorganic constituents from aqueous streams. This process produces a solid or sludge which must then be disposed of by some land disposal technique. Many of the treatment techniques are widely used in industrial practices. Except for a few developmental processes, they have been demonstrated under conditions similar to those at cleanup sites. Their cost ranges from very low in the case of processes like precipitation and settling for the removal of heavy metals to quite expensive for sophisticated techniques for treating organics such as wet air oxidation or reverse osmosis.

Incineration on-site has been virtually unused to date although it is capable of very high destruction efficiencies-in excess of 99.99%. Wastes have been taken off site to be treated by incineration. Future on-site use is expected to remain low. The technique is expensive, requires the installation of complex equipment and needs specially trained operators. Mobile units, that could obviate the long lead times needed to design and construct permanent on-site incinerators, are in various stages of development but have not as yet been used at a cleanup site. Many of the mobile units have low feed rate capacities and would have to remain at the site for many years to dispose of all the wastes. This disadvantage offsets the advantage of rapid startup.

In-situ biodegradation is a relatively new technology still in a state of early development. It can destroy wastes in place and promises to be less expensive than removal and disposal in secure landfills. Like biological treatment, in situ biodegradation may not be able to achieve levels of destruction sufficiently high to meet environmental target criteria. Virtually no data on the performance of specific toxic species exists to verify the validity of the preceding sentence.

The two techniques for gaseous streams, thermal oxidation and carbon adsorption, are widely used in industrial operations and can be easily transferred to cleanup situations. The choice between adsorption or oxidation depends on the particulars at the site. Both are proven and in the same general cost range. Carbon adsorption is better equipped to handle variable inlet conditions.

For inorganic contaminants, neutralization/precipitation in combination with sedimentation and/or filtration is widely used and will continue to be used where inorganic contaminants are found. The techniques are capable of removing heavy metal constituents to very low levels. This approach is inexpensive and can be tailored to a wide range of site conditions. The specialized treatment processes such as cyanide destruction and chromium reduction are commonly applied in industrial applications but may find more limited use at cleanup sites. These processes have been designed for industrial wastes of very well defined characteristics. The wastes for which they are designed are generally found mixed with other contaminants which may interfere with the process, and as a result, may limit their applicability or require multiple processes.

Flotation is a specialized process used to remove insoluble organics and inorganic particulates for aqueous mixtures. The technique is particularly useful for removal of oil and grease and will find application at sites where the contaminated wastes contain these species. Flotation is often used as a pretreatment process to reduce the load on biological treatment. The sludge is produced in flotation can be incinerated or disposed of by land disposal means.

Extraction and solution mining are means to transfer contaminants from soil to an aqueous stream that can be more effectively handled. They are always used with some additional treatment process. There has been little use of these techniques to date. Chemical injection methods are adaptations of other treatment processes to an in situ mode. In these techniques reactants are injected in the soil where they either destroy the organic compounds or force the inorganic compounds out of solution. All of the chemical injection techniques are developmental. They can eliminate the requirement for either excavation or pumping. They are most useful for wastes that are homogeneous since the reactions tend to be quite specific. Permeable treatment beds fall between chemical injection and at-the-surface treatment processes. In these technologies reagents are placed in trenches through which groundwater can flow. They should be inexpensive and would require only limited excavation. They work well for shallow contaminated plumes. Extensive testing is required to develop an appropriate design. The effectiveness is influenced by variations in groundwater flow.

D. Combinations of Technologies

As noted earlier, technologies are used in combinations to achieve performance levels not attainable in simple systems. Systems to handle potential and existing groundwater contamination problems generally combine means to prevent infiltration with barriers or pumps to prevent outward migration. Caps and run-on techniques have been commonly used for the first objective. Up-gradient barriers have also been employed to route incoming groundwater around the contaminated region. Groundwater pumping may also be used to adjust the water table to levels below the contaminated zones. Barriers and pumping can control out migration.

None of these techniques is foolproof, alone. It is very difficult to verify the complete integrity of hydraulic or barrier systems. Groundwater controls are affected by the hydrogeological characteristics at a site. In spite of careful surveys and design procedures, anomalies may exist such that the performance will not achieve the design level. Water table mounding can occur. Inaccessible regions may exist. Small cracks in caps are difficult to find. Windows and cracks in barriers may go undetected until serious problems are observed. And performance may deteriorate over time, as indicated in several of the examples.

Combinations of techniques can realize high levels of performance reliably even if some of the elements have problems. Pumping to control the hydraulic gradient to create flow toward the site can prevent outward migration even if an installed barrier wall becomes permeable or has windows due to installation imperfections. Caps can greatly reduce the flow downward into a site with a circumferential barrier wall and thereby prevent or mitigate the so-called bathtub effect, where the volume inside the barrier fills with water. Eventually the level would build up to create a positive outward hydraulic gradient (or even overflow) such that wastes could permeate outward or flow out through imperfections in the barrier.

Combining solidification or encapsulation with other containment means can improve the overall performance. Solidification and encapsulation are means to isolate the waste on a microscopic level; containment isolates the waste on a macroscopic level. The resistance to migration (leaching and flow) provided by the technologies are additive.

Treatment technologies are similarly often found in combinations. In some cases, with technologies that detoxify or destroy the hazardous components, the performance of a single technology is insufficient to achieve a level of protection considered adequate to protect public health and the environment. For example, conventional activated sludge biological treatment, a relatively inexpensive technique, may (and often) produces an effluent with certain constituents at levels above target concentrations. In these cases, additional treatment steps, such as carbon adsorption, may be required.

For treatment technologies that separate the contaminants from a waste and transfer them to another medium, some additional step (or steps) is always needed. That step may be as direct as depositing heavy metal sludges from precipitation and settling in an off-site secure landfill. In a more complex system, carbon adsorption or fume incineration may be used to capture stripped out volatiles (see example #3, above). Direct discharge to the atmosphere from a stripper may be possible if adequately protective of human health.

The determination of what combinations of technologies is appropriate at a given site has been primarily driven by the broad cost-effectiveness criterion, once an applicable (feasible) set of alternatives has been developed. The broad criterion examines the ability to perform over the period of analysis, that is, what level of protection does the technology provide in the relatively near term, and adds up the costs over that period. Less emphasis has been given to long-term reliability issues and to consequences of transferring the health and environmental risk offsite to other locations or to other on-site exposure routes.

Containment alone can provide high levels of performance, measured by the residual level of risk to the previously exposed population. As noted, combinations of techniques, particularly barriers with hydraulic controls, should function over long time periods. But, in every case, the original hazards are still in place. At some time in the future, it is likely that portions of the system will fail and will have to be replaced in order to maintain the levels of protection. If these future costs are not included in the analysis, the costs of containment systems will be understated. There is very little experience today that provides information on the long-term performance, and it is very difficult to predict such future costs with a degree of confidence anywhere close to that achievable with near-term costs.

Systems that destroy the hazardous components obviate this problem. They simplify the analysis and, more importantly, they achieve permanent levels of protection. There would be little question about the choice of containment versus destructive treatment if this were the only consideration. Destructive treatment may be quite expensive approaches relative to containment. Incineration of large volumes of contaminated soil (such as occurs at some dioxin sites) is generally a very expensive option compared to containment at the site or off-site at a secure facility. Also, destructive treatment may be insufficient to achieve adequately protective output levels.

Treatment processes that transfer the wastes from one medium to another represent yet another type of performance. They may permit the disposal of much of the original volume in an inexpensive but protective manner. Air stripping can leave effluents that may be discharged safely to the environment as vented gases or as recharge or discharged to a surface water body. Precipitation serves the same basic function. The residual sludge is much smaller in volume than the original waste and can be handled by techniques that are more cost-effective.

Unless the complete result of a set of treatment processes is a set of effluents that can be safely discharged to the environment, containment (land disposal) must be employed as a final means of disposal. For metal sludges, a secure landfill is the conventional repository. Offsite disposal is common. In a few cases, on-site disposal in a new secure facility has been considered. In general, the original hazard has been transferred to a new setting where, by design, the risk to human health and the environment is less than that at the site.

Examination of the results of the selection process at actual sites, such as those briefly described in the examples, indicates that combinations of technologies have generally found to be cost-effective. Both kinds of treatment processes, destruction and separation, are being employed. Containment, as a sole means of protection, has been used at a few sites, but is used conjunctively with treatment at most sites.

E. The Effects of Institutional and Cost Factors

The primary criterion for selecting technologies at cleanup sites, as reflected in the National Contingency Plan and in most equivalent state documents, is cost effectiveness; that is, the "lowest cost alternative that is technologically feasible and reliable and which effectively mitigates and minimizes damage to and provides adequate protection of public health, welfare, or the environment." In the Federal decision-making process, this criterion is qualified by the so-called fund balancing provisions of the National Contingency Plan. These provisions require that prospective costs at a given site be balanced against the overall needs for all sites to be cleaned up. In essence, even the most cost effective alternative at a site may be ruled out if the total resource costs is out of line with needs at other sites. Changes to the NCP were being formulated as this report was being completed. These changes would provide additional, more discrete performance criteria.

In reality, however, there are other factors which appear to influence the selection of particular technologies. These factors arise out of the idiosyncrasies of the decision-making process itself, and of the characteristics of the many different interests involved. Although these factors are quite different in nature, they have been denoted institutional factors for the purposes of this discussion. The next several paragraphs describe several of these factors, some of which involve the way in which costs enter the analysis, in general terms. Anecdotal data, where available, are included to illustrate the impact of the particular factor.

Much of the above discussion of the individual technologies has focussed on technical or performance related topics, i.e., factors which bear on the effectiveness half of the major selection criterion. The eventual choice also depends on the cost. As noted earlier, it is very difficult to generalize discussions of the applicability and effectiveness of technologies because they depend so much on waste and site characteristics, and further because unique and often complex combinations of technologies are employed at each site. It is at least as difficult to generalize the cost attributes of individual technologies and of combinations. There has been considerable variability, early in the remedial action program, in the cost elements that have been included in the analysis. To compare alternative options fairly and uniformly, it is necessary to use a set of cost elements reflecting equivalent performance. That is, with a common initial and end point defined in terms of some state in the project life.

Costs can be identified and collected according to many schemes. The list in Table 8 captures most of the significant items over a project's life. For containment that life could be indefinite; for treatment, projects are designed to end after a finite period.

The items marked with an asterisk in Table 8 are generally included in analyses of both containment and treatment clean-up alternatives. For treatment systems, estimates of these cost elements is generally quite straightforward. Project life is usually short; a few years is common. Assuming proper design, i.e., that the system will operate as projected, all the cost elements can be estimated quite accurately. Decommissioning costs have been less consistently included and are more difficult to estimate. No long-term costs are involved as the project is expected to end with an acceptable level of residual contamination present.

The situation for containment is quite different. Since the hazards remain in place indefinitely, any future costs associated with maintaining the original level of protection should be included. Such costs include monitoring and major repairs. O&M costs, including monitoring, are usually considered only for a relatively short time, often 20-30 years. Major repairs and restoration or treatment, in terms of or in addition to repairs that are very likely to occur at some indeterminate future time, are not included.

These nonincluded items can be substantial, and at some number of years in the future would exceed the total costs for the first 20-30 years, the usual time frame for the cost analysis. Discounting or computing the costs on a present value basis would, with conventional discount rates (currently around 10%), effectively ignore costs much beyond the 30-year period. This practice moots such questions as should the problem be passed to future generations (see further comments in the next chapter).

TABLE 8

REMEDIAL ACTION COST ELEMENTS

Design*

Field data
Laboratory/Pilot Testing
Design/Modeling

Capital Equipment*

Purchased Items
Major Rentals (Mobile Incinerator, Packaged Adsorbers,
etc.)

Installation*

Labor
Machine rental
Materials

Operations and Maintenance*

Labor
Supplies
Fuel and Power

Monitoring

Disposal of Treatment Residuals

Major Repairs (including future treatment)

Decommissioning

* Generally included cost elements.

On the other hand, proper application of present value analysis for the 20-30 year span provides a fair comparison of containment approaches, which tend to have high initial costs compared to total annual costs over the project life, to treatment approaches which often exhibit the opposite behavior. The total O&M costs, disposal costs, etc. assumed over the project life may exceed the initial costs.

One factor that has influenced the choice of technology is related to the cost-sharing provisions of CERCLA. For State and Federal lead sites, the Federal government generally pays 90% of the capital costs and costs for the first years operation. Paying for subsequent operating and maintenance costs, on the other hand, is entirely the responsibility of a State. This is very similar to the situation governing cost sharing for publicly owned treatment works funded under the Clean Water Act. The consequences are fairly straightforward. The Federal government will push for technologies with low capital costs and high O&M costs; states will argue for the converse.

For containment technologies, the total cost of a project tends to be dominated by the initial costs. For many treatment technologies this is not the case, even though capital costs may be quite high. While some states may keep their arguments on the subject implicit, some states have expressed very strong policies against solutions which involve substantial operating and maintenance costs (personal communications, Charles Faulds, Texas Dept. of Water Resources; Bob Cowles, Illinois EPA). Evolution has led to a more joint process so that one-sided decisions are not likely. Nevertheless, this factor will continue to influence the various players.

The above problem may be exacerbated by regulatory requirements that relate to the degree to which wastes must be treated prior to disposal or discharge. At present, there is considerable uncertainty as to the applicability of Federal and State environmental regulations to activities at cleanup sites. The choice of which environmental standards apply to, for example, discharges from water treatment processes would have very strong effects on the operating and maintenance costs of systems, but often less significant effects on the initial costs. In one case in Michigan, the imposition of effluent limitations rather than water quality standards added half a million dollars to the capital costs of a carbon adsorption system and \$350,000/year to the operating and maintenance costs relative to the cost of a system meeting water quality standards (personal communication, Andrew Hogarth, Remedial Action Section, Michigan).

If RCRA or equivalent regulations at the State level permits are deemed to be required for operations at cleanup sites, there may be further discrimination against technologies which are considered to be difficult to permit. Most permitting processes at state levels involve public participation at some stage. Local opposition to certain clean-up technologies such as on-site incineration, have been much greater than others such as biological treatment or carbon

adsorption. (Personal communication, Lee McNew, Pernco, Oak Ridge, Michigan). This issue is largely conjectural at present because the policies on "how clean is clean" have yet to be finalized, and only in a few cases have permits been required at cleanup sites. But if the experience parallels that observed so far in RCRA permitting procedures, widely differing public acceptability for various technologies would be expected to influence the choice of technology. Uncertainty in the permitting process may also influence the technological choice in other manners. The use of a mobile incinerator was considered for a cleanup site in Massachusetts but was dropped from the list of potential technologies because the State had placed a moratorium on consideration of mobile incineration generally. They were in the process of promulgating regulations and did not want to consider any technology that would require permitting (personal communication, Rich Cavanaro, EPA, Region I).

The budget process in most states creates a bias against alternatives that have costs spread out over a number of years. Most states can only budget year by year and many have no authority to operate cleanup projects through trust funds or bond proceeds. Thus, states cannot guarantee that funds will be available to continue operations beyond the first year or two of a project. Local jurisdictions may be concerned that the State will lose interest in the project and default on its commitments, leaving that jurisdiction with the cost of operations. This issue has arisen at a site in Battle Creek, Michigan, where treatment of groundwater with carbon adsorption and air stripping is being weighed against the development of an entirely new drinking water supply well field. The City believes that the State will default on its commitment to meet future O&M obligations, and has argued against the treatment technologies and for the well field (personal communication, John Dikines, EPA, Region V).

The last issues are related to the way in which the program is being implemented at the Federal level. The EPA and most state agencies rely heavily on contractors to carry out the feasibility and alternative selection studies. At present, because of public and political anxieties, there is tremendous pressure to move through the analytic phases quickly. The time pressures may inhibit thoughtful and careful examination of all alternatives. Consulting firms by their nature are conservative and are under considerable pressure to produce early results, sound and reliable solutions, and to control their costs. Developmental technologies would suffer under such circumstances. Technologies which require extensive lab and field tests would also appear less desirable. There are little hard data on the effect of these practices, but several respondents expressed their belief that time and public pressures, and the intrinsic conservativeness of the process has inhibited the evaluation of innovative approaches at the expense of the more conventional containment techniques (personal communication, John Dikines, EPA, Region V; John Wardell, EPA, Region VIII).

F. Conclusions

In addition to the comments pertaining to the individual technologies, the following several general conclusions appear relevant.

There is a wide variety of individual technologies presently available both for containment and also for treatment. These individual techniques can and are being used in combinations ranging from systems based primarily on containment to systems primarily using treatment.

Treatment processes are often used in combinations to handle the complex and mixed wastes found at many clean-up sites. Successive treatment by several technologies may be required to reduce containment levels to comply with criteria and standards set to protect human health and the environment.

Most of the technologies are relatively untested in clean-up situations. Little or no long term performance data is available for containment systems. Extensive testing during selection and design is generally needed, and similarly, careful post-installation monitoring should be carried out. The first round of actions that have been completed or are up and running are serving to demonstrate the efficacy of many of these techniques as well as serving the primary function of protecting health and the environment.

Institutional considerations are important in the selection process, and may be the primary determinant in some cases. Present technical criteria are not sufficiently explicit to treat issues such as long-term reliability and future costs.

IV. OUTLOOK

A. The Balance Between Containment and Treatment Apparatus

The primary purpose of cleanup technologies is to reduce the hazards posed to human health and the environment at uncontrolled waste disposal sites to acceptable levels. The hazards may be current wherein populations are now exposed to contaminants in air, water or soils, or future where continued migration of the contaminants would create such exposures.

The relative usefulness of each technology depends on several implicit characteristics of acceptability. The basic criterion in the Federal regulation governing the choice of technologies, the National Contingency Plan, is cost-effectiveness. The effectiveness term in this equation relates to the degree of protection of human health and the environment. No absolute level defining the performance of the remedial technologies has been included, but the minimum level of protection must be adequate. The standard against which the choice is made is relative. When each appropriate technology at a site is arrayed relative to all of the others, the technology providing the greatest effectiveness in hazard mitigation expressed in terms of risk reduction, degree of contaminant removal, or some other similar measure is to be chosen. This implies, that, for example, technologies which can reduce exposure by 90% may be preferred to technologies which can reduce exposure by 99% if the costs of the latter are significantly greater than those of the former, and if the risks posed to human health and the environment at the 90% reduction level are acceptable.

The Environmental Protection Agency is presently grappling with the indefiniteness of this criterion. One outcome of this analysis, generally referred to as "How clean is clean?", may be the imposition of some minimum performance standards, expressed as percent reduction in exposure, for example, or requirements that the technologies achieve reduction of contaminants below levels prescribed by existing environmental standards or other similar criteria. Some of the technologies discussed herein may not be capable of achieving performance levels demanded by the imposition of the most stringent criteria. The projections below dealing with applicability of technologies will have to be revised if the policies do in fact contain such criteria. Clearly, only those technologies singly and in combinations capable of providing higher levels of required performance will survive such a revision process.

The second implicit factor involves time. The National Contingency Plan is silent with respect to the time period over which the cleanup technologies are to be effective. Whether intended or not, the framework for analysis in support of the selection process has focused on near-term effectiveness. Treatment technologies are generally designed to reduce contaminant levels to the desired end point within periods typically of a few years, possibly as long as ten years, and only rarely, if ever, much longer periods. Containment technologies, conversely, must function indefinitely since the contamination remains at the site or at some off-site location. If containment technologies will, in fact, function indefinitely, then it is fair to compare treatment approaches directly with containment approaches.

But if containment systems cease to function as designed after some period of time and can no longer keep hazards at or below the desired level, then, it is appropriate to compare the two approaches only for the period in which the containment approach functions properly. A fair comparison of the two approaches must, in that case, include consideration of the additional technologies and costs that would be employed at that future point in time to achieve the desired level of performance as discussed above. At present, in examining alternatives, containment technologies are generally considered to function indefinitely. No provisions for future action are usually included in the analysis except to reflect costs of normal maintenance. Even if such considerations were included in the analysis, the present value or discounting of costs far into the future would add a negligible increment to the basic cost of containment technologies.

The implication of these arguments is that the basic choice between containment and treatment technologies rests on the costs incurred in the present time frame, that is, over the next several decades. Containment technologies are generally less expensive than treatment technologies, and so, as shown by experience so far, that group of approaches has been used more extensively than has the set of treatment technologies. Since there is as yet, very little long-term experience with containment technologies used in the context of remedial action, virtually no data exists that can be used with confidence to predict the period of time over which the technology will be effective. It is more reasonable to assume that none of the approaches are indefinitely fool-proof. With this assumption the balance between these two basic approaches rests in part on how far the present generation of decision-makers will go in passing the next phase of this problem to future generations.

Careful present value analysis, as is becoming the practice, will tend to reduce (or reverse) the apparent cost advantage of many containment approaches resulting from the cost analyses at the early remedial projects.

The balance is even more complicated in certain cases where present treatment methods are not considered cost effective. They may be very expensive, unreliable, or incapable of achieving the level of performance deemed to be adequate. But, if there is some expectation that acceptable processes will arise in the future, then containment could be viewed as an interim measure, deferring the final decision until a more appropriate technology becomes available. Such a decision should include consideration of the future cost of the treatment process relative to the perhaps excessively high cost of a current technology, and of the costs and risks of alternate options if such technology does not materialize. This option has been selected as the preferred alternative for cleaning up dioxin-contaminated soils from a number of sites in Missouri.

B. Containment Technologies

The main factors that appear to influence the selection of containment approaches are:

- o applicability
- o composite effectiveness
- o confidence
- o cost
- o capital to O&M cost ratio

Applicability refers to the extent to which the approach can be used without being limited by site or waste characteristics. Effectiveness describes the ability to achieve high levels of leak-tightness. Confidence relates to the designer's ability to predict performance. Cost is a relatively poor predictor of choice because it is so site specific. The cost of a particular technique can vary over more than an order of magnitude depending on the site. The ratio of capital costs to O&M costs is, on the other hand, more constant for each technology, and may influence the choice depending on the primary institutions responsible for clean-up.

These factors have been used to score the various clean-up technology. The scoring categories and levels are shown in Table 9 and the results of the evaluations are shown in Table 10. The projected use is described as:

- o extensive
- o moderate
- o limited
- o nil

The projected level of use was determined by a largely subjective evaluation based on the several determining factors.

TABLE 9

FACTORS USED TO RATE CONTAINMENT TECHNIQUES

APPLICABILITY

- 1 - Very broadly applicable; little or no site dependency
- 2 - Broadly applicable; some sites unfavorable
- 3 - Limited to sites of specific characteristics

EFFECTIVENESS

- 1 - Can produce "leak-tight" containment
- 2 - Can reduce migration - some leakage likely
- 3 - Used as supporting technique in conjunction with other elements

CONFIDENCE

- 1 - Well proven - long-term effectiveness - high
- 2 - Well proven - long-term effectiveness - unknown
- 3 - Limited experience; used in other applications
- 4 - Developmental; little data

COST FOR FUNCTION PROVIDED

- 1 - Low
- 2 - Normal
- 3 - High

CAPITAL TO O&M COST RATIO

- 1 - Capital higher than O&M
- 2 - Capital about same as O&M
- 3 - Capital lower than O&M

Assuming that the present basis for choosing clean-up approaches and that the players involved do not change, some combination of containment technologies will continue to be used extensively. One or more of the techniques will almost certainly be used at every site. Slurry walls, and hydraulic systems (walls) appear to be the long-term favorites used individually or in combination. Surface seals also should continue to see widespread application, but mainly in combination with a barrier or hydraulic system. Seals may continue to be used as a quick-fix, i.e., to reduce out-migration due to infiltration while more permanent solutions are designed and put in place. Run-on controls will continue to be widely used as a means to support the operations of the primary containment system.

Grout curtains should be used moderately in the future. The opportunities for applications of this technique are more limited by site requirements than those of slurry walls, but the expected effectiveness can reach the same level. The vibrated beam technique has several advantages, but is not well known to design engineers and construction operators and consequently will probably not be used as widely as its technical characteristics suggest. Sheet piling may be used at a limited number of sites, but generally do not display the combination of desirable properties as the previous three techniques. Block displacement is much too early in the development process to receive serious consideration as a containment technique presently.

Solidification methods should find moderate applications in conjunction with barrier containment and surface seals. Combinations are capable of reliable performance far beyond that of either component. As a technology used solely, solidification will probably have very limited application. Vitrification, like block displacement, is at a very early stage of development, vis a vis, hazardous waste applications and is not expected to be used in the near future.

C. Treatment Technologies

A similar set of exhibits have been prepared for treatment techniques. The factors (Table 11) are essentially the same, although the levels are described differently for a few categories. Secondary disposal requirements have been added. Some treatment techniques, such as carbon adsorption, create a residue that must be managed as a hazardous waste. Some processes are basically separation techniques and the resultant concentrated waste streams must be treated or disposed of in a secondary stage. Many of the treatment processes are applicable to only organic or only inorganic compounds.

The results are shown in Table 12. For many of the organic contaminants, carbon adsorption appears to be the most popular clean-up technique in use. Since the organic species for which it is most attractive are often the major problems at clean-up sites, it should continue to be widely used. Carbon adsorption, in combination with other practices, can clean up groundwater to meet high

TABLE 10

FUTURE USE OF CONTAINMENT TECHNOLOGIES

<u>Technique</u>	<u>Applicability</u>	<u>Effectiveness</u>	<u>Confidence</u>	<u>Cost</u>	<u>Cap/OSM</u>	<u>Projected Level Of Use</u>
<u>Barriers</u>						
Slurry Wall	1	2	2	2	1	Extensive
Grout Curtain	2-3	2	2	2-3	1	Limited
Vibrated Beam	2	2	2-3	2-3	1	Moderate
Sheet Pile	3	2	2	2-3	1	Nil-Limited
Block Displacement	3	2	4	3	1	Nil-Limited
<u>Hydraulic Controls (Wells)</u>						
Subsurface Drains	1	1,3	1	1	3	Extensive
Runoff/Runoff Controls	2	1	2	1	2	Moderate
Surface Seals and Caps	1	3	1	1	2	Extensive
Solidification	1	2,3	2	1	1	Extensive
Encapsulation	2	1,3	3-4	2	1	Limited-Moderate
Vitrification	3	1,3	3	3	1	Limited
	3	1	4	3	1	Nil

TABLE 11

FACTORS USED TO RATE TREATMENT TECHNOLOGIESAPPLICABILITYClass

- Or - Organic compounds
In - Inorganic compounds

Range

- 1 - Broadly applicable to compounds in indicated class
2 - Moderated applicable; depend on waste composition;
concentration
3 - Limited to special situations

EFFECTIVENESS

- 1 - Highest levels available
2 - Output may need further treatment; may have pockets
untreated (in-situ)

CONFIDENCE

- 1 - Well proven - easily transferable to site cleanup
2 - Well proven - but not in clean-up settings
3 - Limited experience
4 - Developmental; little data

COST FOR FUNCTION PROVIDED

- 1 - Low
2 - Normal
3 - High

TABLE 11

FACTORS USED TO RATE TREATMENT TECHNOLOGIES
(continued)

CAPITAL TO O&M COST BASIS

- 1 - Capital higher than O&M
- 2 - Capital about the same
- 3 - Capital lower than O&M

SECONDARY TREATMENT OR DISPOSAL

- 1 - None
- 2 - Minor
- 3 - Major, but does not require hazardous waste techniques.
- 4 - Basically a separation process; must be used with subsequent hazardous waste treatment or secure disposal step

TABLE 12
FUTURE USE OF TREATMENT TECHNOLOGIES

Technique	Applicability	Effectiveness	Confidence	Cost	Secondary Projected Level	
					Cap/O&M	Disposal Use of
Biological Treatment						
Chemical	Or, 1-2	2	1	1	1-2	3 Moderate
Neutralization/ Precipitation	In, 1	1	1	1	2	4 Moderate-Extensive
Wet Air Oxidation	Or, 2	2	2	3	1-2	1 Limited
Chlorination (CN)	In, 3	1	2	2	2	1 Limited
Ozonation	Or, 3	2	3	3	2-3	2 Nil
Reduction (Cr)	In, 3	1	2	2	2	3 Limited
Physical						
Carbon Adsorption	Or, In, 1	1	1	2	2-3	2-3 Moderate-Extensive
Sedimentation/Filtration	Or, In, 1	1	1	1	2-3	4 Moderate-Extensive
Stripping	Or, 2	1	1	1	2	4 Moderate
Flotation	Or, 2	2	1	1	1	4 Limited
Ion Exchange	In, 3	1-3	3	3	3	4 Nil
Reverse Osmosis	Or, In, 3	1-2	3	3	3	4 Nil

TABLE 12

FUTURE USE OF TREATMENT TECHNOLOGIES

(continued)

<u>Technique</u>	<u>Applicability</u>	<u>Effectiveness</u>	<u>Confidence</u>	<u>Cost Cap/06M</u>	<u>Secondary Disposal</u>	<u>Projected Level of Use</u>
<u>Gas Stream Controls</u>						
Thermal Oxidation	Or, 1	1	1	3	3	Limited-Moderate
Carbon Adsorption	Or, 1	1	1	3	2-3	Limited-Moderate
<u>Incineration</u>						
On-Site	Or, 1	1	2	3	3 ^a	Limited
Off-Site	Or, 1	1	1	3	3 ^a	Moderate
<u>In situ Biodegradation</u>						
	Or, 3	2	3	2	3	Limited
<u>Extraction</u>						
	Or, In 3	2	4	2	3	4
<u>Solution Mining</u>						
	Or, In 3	2	4	2-3	3	4
<u>Permeable Treatment Beds</u>						
	Or, In 3	2	3	2	1-2	1-3 ^b
<u>Chemical Injection</u>						
	In 3	1-2	4	2	3	1

Notes:

a. Must dispose solid residues.

b. Depends on reactive material used.

environmental and health standards. Stripping in combination with incineration of the vapors can reduce residual levels of highly volatile compounds in water to very low levels, but does not work well with less volatile, hazardous species. Its use is expected to be less than carbon systems.

Biological treatment, and to a lesser extent, wet air oxidation, will find use at sites where moderate to high concentrations of organics are present. Both are more cost effective for relatively concentrated aqueous organic streams than is carbon adsorption. Conventional biological treatment technologies may find applications at sites where groundwater is extracted, treated and reinjected to control hydraulic gradients. In such cases, meeting extremely stringent discharge standards would not be as critical as the case for treating groundwater that may end up in a useable aquifer or surface water supply. Below surface, in-situ biodegradation techniques have been claimed to be able to achieve the same general level of treatment as surface mounted systems, at potentially less cost. This technology is at a relatively early stage of development and has been used in only a few cases to date. One of these is at a site where the owner developed an in-situ process to handle his own contamination problems springing from a leaky underground spent solvent storage tank. Such in-situ methods are generally considered as developmental techniques; their use will be limited under NCP selection procedures which avoid relatively unproven methods. Surface application of special organisms, on the other hand, is more accepted as a proven technique.

Off-site incineration has been used to treat bulk organic liquids removed from a site during initial clean-up operations. After initial removal at many sites, there still remain large quantities of wastes and soils contaminated with organic (and inorganic) compounds. These solid materials, if untreated, will act as continuous sources for as long as the wastes are available to leaching and migration processes. Incineration on-site (and off-site) should, in the near future, become moderately applied at clean-up sites. Technically, the potential use would appear to be extensive as incineration is very effective at reducing organic contaminant levels to nil. But off-site incineration is expensive and transportation of large amounts of materials is costly and risky. The development of reliable, tested mobile systems for on-site applications has been slow. Permitting uncertainties, exacerbated by broad public opposition, have caused project managers to be reluctant to propose incineration. The economics of permanent installations that would be used, perhaps, only for a few years are poor. In any case, however, use of incinerations both on site and off site should increase in the near future.

Developmental concepts for treating contaminated soil such as ultra high temperature destruction (OTA, 1983), or photolysis combined with ozonization may find application at a limited number of sites, for example, where dioxins are present, where the hazards are so great that the high levels of performance theoretically achievable outweigh the resistance to use new and relatively expensive technologies.

Technologies for treating aqueous streams containing inorganic contaminants can be drawn from a well demonstrated, widely used base. Conventional techniques such as precipitation, settling, and filtration to produce a very clean water stream and a sludge containing heavy metal residue can be used at virtually all sites where such a problem exists. The specialized techniques such as cyanide destruction or chromium reductions can be used where these specific pollutants show up and where other contaminants would not interfere. Overall, these special circumstances have limited occurrence so the techniques should, be found, similarly only at limited sites. Few applications of ion exchange are expected. This technique is excellent in situations where a particular inorganic compound is to be recovered, usually as part of a process where inlet conditions are carefully controlled.

The in-situ methods, solution mining and injection and the related approaches, permeable treatment beds and extraction are all at an early stage of development. None are expected to be used beyond trials in the near term. The in-situ methods are attractive because they avoid the need to excavate contaminated soils or produce a more easily treated liquid stream than the solids in which the contaminants were originally interspersed.

D. Changing The Outlook

The outlook for application of the various technologies, treatment vs. containment, or the use of specific technologies is based on assumptions about current selection criteria. If any of the criteria change or if the institutional factors shift in the future, the situation could change substantially. This section examines the potential impact of several departures from current norms.

The most critical issue is tied up with the effectiveness of the remedy. As noted earlier, effectiveness as expressed in present regulations and policies is a relative measure. No environmental standards or target levels of risk are mentioned. In essence, the process of selection has been a site-by-site process, qualified only by overall fund balancing considerations. Current debate on the "how clean is clean" issue has been vacillating (during the period of this study) from retaining the status quo to establishing "applicable and relevant" standards with some set of exemptions to provide flexibility. Any change is likely to move toward the imposition of standards and to a preference for primarily treatment combinations rather than primarily containment options.

Classification of sites according to the hydrogeological and other technical features and to the degree of hazard at the site would have a similar impact. Schemes could be developed that would designate a class of clean-up technologies (and time frame) depending on the factors. At sites with groundwater contamination beyond the original disposal site and where a drinking water supply for some minimum population has become or may become polluted, treatment might be required. Containment could be used only to support treatment but not as an independent solution. At the other end of the hazard spectrum, containment as a sole means might be acceptable at sites with limited out-migration potential and where drinking water supplies are not threatened. At most sites combinations of containment and treatment would continue to be used.

Any implicit or explicit requirement to clean up groundwater would obviously call for the application of treatment technologies. Carbon adsorption, because it can achieve high purity, is effective for a large number of containment species, and has been used to purify drinking water (there should be reasonable public confidence in this technique), is likely to become the technique of choice at many sites, alone or in combination with other treatment techniques. If the provision of alternate water supplies is permitted as an exception where small number of families are involved and treatment costs are very high, then containment will continue to be selected.

A shift in cost accounting practices to allow cost-sharing for continuing as well as initial costs would reduce some resistance to treatment as long as the primary players are federal and state governments. This factor will become less important if the trend to turn over the decision and implementation process to the private parties responsible for the damages continues. Corporate decision-makers, influenced by legal advisors often opt to reduce future liability as much as they can. The more permanent treatment approaches should be favored. Further corporate financial decisions are frequently based on a discounted or present value basis. Treatment will generally look more favorable because this accounting practice amplifies the impact of early costs relative to those occurring down stream. Present value computations are becoming more common in Federal and state cost analysis.

Developmental techniques, without extraordinary efforts by the scientific and business entrepreneurs who stand behind them, will probably continue to find only limited applications. A federally supported set of demonstration projects designed to determine performance and costs under field conditions could reduce the barriers that appear to inhibit the introduction of new solutions.

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